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Multi-Agent System Based Distributed Voltage Control in Distribution Systems

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ABSTRACT OF THE MASTER'S THESIS

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Distribution System is a standout among the most complex entities of the electric power grid. Moreover, voltage quality sustainability till customer premises, with the introduction of Distributed Generation (DG), is one of the most frenzied control areas. Previously, SCADA in cohesion with Wide Area Measurement Systems (WAMS) was a dependable control strategy, yet as the ever growing and complex distribution system is advancing towards the Smart Grids, control strategies are becoming more and more distributed in spite of the centralized one.

A detailed literature review of the voltage control methods ranging from the centralized one to the fully distributed agent based control is conducted. In the light of the previous researches, a distributed voltage control based on Multi-Agent System is proposed, as the agents based control strategies, are becoming well known day by day, due to its autonomous control and decision making capacity. To make the proposed algorithm fully distributed, token transversal through the network and agents communication to remove voltage violation over least correspondence and measurements of the system, are utilized. Following instant voltage control at the load nodes, a penalty function is employed to keep the voltage value curve throughout the network as close as possible to the nominal, with minimum network losses and minimum voltage damage.

The authentication of the devised control algorithm is acknowledged by utilizing a Greenfield distribution Network, which is based on the realistic loading data. Agents and the controlling logic are codded in Matlab ® programming software. A sensitivity analysis is performed based on DG penetration to have the complete overview of the proposed methodology. The principle objective of the technique is to keep the voltage value within the standard limit of $\pm 10\%$ of the nominal, at all load nodes while instantly utilizing voltage control entities like DGs, Static VAR Compensator (SVCs) and On-Load Tap Changer (OLTC). In addition, the optimization of network losses and voltage level close to nominal is to be accomplished by the penalty function implementation.

Keywords: Voltage control, Distributed Voltage Control, Power Quality, Multi-Agent Systems (MAS), Distributed Generation, Smart Grids

Preface

Thanks to almighty God, the most gracious and merciful, Whose guidance helps me through every walk of life.

This master thesis was carried out in the research group of Power Systems, in the school of Electrical Engineering, at Aalto University.

First and foremost, I would like to express my deepest gratitude to my supervisor **Prof. Matti Lehtonen** to give me an opportunity while having faith in my abilities. It was such an honour to work under his guidance. And thanks to **M.Z.Degefa** and **Farhan Hameed Malik** for the valuable discussions and instructions that were quite helpful and were the defining moments for the various goal accomplishments in my thesis completion. Especially, thanks to Zubair Shahid for helping me in compiling and proof reading of my thesis.

Finally, I would like to thanks, my family for standing by me through thick and thin and for always being there for me, especially my parents who were the constant source of motivation.

Espoo, Finland.
13.10.2015

Ammar Arshad

Contents

List of Abbreviations

ACVC	Automatic Compensation Voltage Control
ACL	Agent Communication Language
AVC	Automatic Voltage Control
AMS	Agent Management System
CVC	Centralized Voltage Control
DF	Directory Facilitator
DG	Distributed Generation
DNO	Distributed Network Operator
DVC	Distributed Voltage Control
DMS	Distributed Management System
EMS	Energy Management System
FFNN	Feed Forward Neural Network
FIPA	Foundation of Intelligent and Physical Agents
GA	Genetic Algorithm
LA	Load Agent
LDC	Line Drop Compensation
LP	Linear Programming
LRT	Load Ratio Transformer
MAS	Multi-Agent System
MLDC	Multi-Line Drop Compensation
NLP	Non Linear Programming
OLTC	On Load Tap Changer
OLTCA	OLTC Agent
PFC	Power Factor Control
PV	Photo Voltaic

QCA	Q-Control Agent
SCADA	Supervisory Control and Data Acquisition
SCB	Shunt Capacitor Banks
STATCOM	Static Compensator
SVC	Static VAR Compensator
SVR	Step Voltage Regulator
VC	Voltage Control
VSR	Voltage Support Request

Chapter 1

Introduction

1.1 Background

In the past decade or two, voltage profile sustainability within standards is a major topic among Distribution Network Operators (DNOs) and the ever changing and growing complex distribution system are the defining constraints to the voltage quality. Voltage value delivered, within permissible standards, to the customer premises is considered being one of the hurdles that every utility company wants to overcome. To maintain perfect sine wave and voltage value close to nominal is really challenging, due to aspects like the load unbalance, distribution line impedance, DG infiltration in the distribution system, non-linear loads etc. Indeed, a comprehensive study of elementary causes and mitigated solutions regarding the voltage profile improvement is required.

Distribution network voltage reliability and controlling strategy's robustness and latency are of prime importance for DNOs. In the past, the power system had only unidirectional flow of power and the voltage drop was the main issue, while with the introduction of Distributed Generation (DG), system is becoming active. In the future, some resources' like batteries, fly wheel storage and electric vehicles are also going to be introduced in the conventional system, which calls for the complete overhauling of the control strategies. Irrespective of the network state (active or passive), voltage value within statutory limits with minimum losses is of great value. As the power sources are diversified by the introduction of (DG), power system is advancing towards "Smart Grid" that not only utilizes DGs but also the traditional power production and distribution facilities.

As DGs are being introduced at various points in the network, in the form of small units, depending upon the availability of intermittent sources, the bidirectional flow of power becomes inevitable. DG proliferation in the distribution system not only increases the losses but also causes the voltage rise problem, which needs to be taken care of. Therefore, the voltage control devices of the distributed system like Static VAR Compensator (SVCs), On-Load Tap Changer (OLTC) at the primary substation and DG reactive power capability are to be utilized in a reliable and hefty manner.

1.2 Motivation

The voltage fluctuation problem is inherent in the distribution systems with the integration of the intermittent DG resources. Different control entities are to be controlled to successfully mitigate the voltage level problem. Centralized Voltage Control (CVC) system such as Supervisory Control and Data Acquisition (SCADA) optimally utilizes the control entities but at the expense of time that should be very short in voltage level related problems. However, application of Wide Area Measurement System (WAMS) in cohesion with SCADA makes the CVC the best possible solution.

Yet, the powerful central control unit, extensive measurement throughout the network and strong communication layout leads to the limitation i.e. single point failure. Moreover, as the number of nodes is increased, which are being remotely controlled, computational overhead becomes immense.

To provide least latency in voltage control contingencies of distribution system, Distributed Voltage Control (DVC), based on Multi-agent system (MAS), is being researched, which tries to come up with the optimum solution, utilizing least data measurement capability of the system. Communication between agents, for execution of control strategies without the consent of the central control system makes the whole voltage management system truly autonomous. Distributed monitoring and processing units associated with agents can easily tackle the problem of computational and communicational saturation, which is innate in CVC.

1.3 Methodology

In this thesis, the approach that is being proposed is intended to use the control entities to their fullest with minimum latency, minimum communication among devices and occasional central control system supervision. A novel but simple approach introduced, utilizes the autonomous behaviour of agents and their communication platform for reliable control.

Basically, the system is divided into several control regions, dependent on the placement of control entities; each controlling entity is concerned about the nodes that are downstream to its vicinity. Agents are associated with each load node and with control devices, to properly control and monitor respective action areas. Mainly, the reactive power capability of DGs and SVCs (that are now abundant in the power system) is used for instant control requirements. Moreover, an iterative method of token transversal through the distribution network, with the knowledge of previously visited nodes as well as the permission for the respective nodes to contact other agents for the voltage control procedure is used. However, after voltage controlling procedure, loss minimization is employed by the implication of a simple penalty function.

After devising a control algorithm, to check the validity of the idea, a case study is conducted, consisting of all the controlling individuals and voltage fluctuations due to DG penetration. DC power flow is conducted for nodal voltage values. The algorithm and agents are coded in MATLAB with some assumptions related to agent's structure and communication design. Notably, various DG penetration levels are studied while considering the power output constant. Nevertheless, the load data of the nodes is based on realistic measurements of a Greenfield network system.

1.4 Thesis outline

The thesis consists of seven chapters in total. Chapter 1 gives the brief introduction related to background, thesis motivation and the methodology that is utilized. Chapter 2 presents the standard for voltage value and a preview of the controlling devices that can be or were previously being used for voltage related problems. Chapter 3 formulates the problem statement, comprises equality and inequality constraints and defines the objectives that require optimization. Moreover, the problem mitigation approach adopted in the previous researches for tackling the problem is also reviewed in this chapter. In Chapter 4, different voltage control architectures are previewed, starting from Centralized Voltage Control (CVC) to fully distributed agent based control systems.

In Chapter 5, novel approach to distributed voltage control, based on Multi-Agent System (MAS) is explained in complete detail. Chapter 6 provides the case study and the results that are obtained from the approach taken for voltage control. Chapter 7 concludes the thesis with the brief overview of findings and in short, gives some suggestions for the future aspects of the conducted research.

Chapter 2

Voltage Value & Control Auxiliaries

2.1 Voltage Magnitude

Keeping the voltage value within acceptable range is the foremost duty of Distribution Network Operators. According to standards EN 50160,

"The nominal voltage value V_n is taken to be $230V$. For $10min$ RMS value, the nominal acceptable range of voltage, 95% of the time ought to be within $\pm 10\%$ range and $+10\backslash -15\%$ during the entire monitoring time [1]."

For these sustainable values, different instruments and voltage control mechanism are used by DNOs. Notably, in distribution systems resistance cannot be neglected in contrast with the transmission system and the reactive power flow from generation to sinks causes additional heating in the lines and is a constant source of the voltage drop. Thereupon, voltage drop mitigation is quite a challenge; to keep the voltage value within range at the farthest end in the distribution system. With the increasing number of Distributed Generation, the distribution network is more prone to voltage level violations, mainly voltage rise in the integration node. DG has transformed the existing passive distribution networks to the active ones. Distribution networks are not designed for the bi-directional flow of power. These problems call for the new voltage controllability measures, within distribution networks, which are reliable.

2.2 Voltage Control Auxiliaries

Previously, passive methods for voltage control were used, but as the networks are becoming more active day by day, with the penetration of DGs in the distribution system, active voltage control methods are also being examined thoroughly. For instance, DGs require conductor size increase or new line enforcement for the voltage rise problems. These network enforcements require a lot of financial support and are quite laborious for DNOs. So they usually abstain from taking such measures. New research is mostly directed towards the active network management that leads towards smart grids, which is quite a running topic in the research circles these days. The equipment and methods that are commonly used to avoid voltage level violations are:

- On Load Tap Changer (OLTC)
- Shunt Capacitor Banks (SCBs)
- Step Voltage Regulators (SVRs)
- Static VAR Compensators (SVCs)
- The Reactive and Real power control of DGs

2.2.1 On-Load Tap Changer (OLTC)

Traditionally, the OLTC is expedited for voltage control in the distribution system. OLTC are commonly equipped with Automatic Voltage Control (AVC) relays that are capable of measuring the voltage on the low voltage side of the transformer and compare it with the voltage set points for the tap changing mechanism. OLTC is also supported with Line drop compensation (LDC) operation which is known as voltage compounding. By using the voltage measured on the secondary of the transformer, that in turn gives the current value, is used for the voltage drop measurement till the load point. This method requires no communication between the load point and the control point [2].Voltage is regulated by OLTC, in discrete steps rather than continuous regulation.

LDC mechanism was reassuring till the time when Distributed Generation was not introduced in the distribution system because it uses the hypothetical value of the impedance and current through the feeder to measure the voltage drop compensation factor. As the load is becoming more and more diversified and unbalanced, it is becoming quite difficult for LDC to operate properly. For accuracy purposes, Multi-Line Drop Compensation (MLDC) strategy can be adopted that is explained in [3]. The method not only used the diversified load data but also takes into account the effect of DG power input into the system.

The main considerations in OLTC are voltage within statutory limits and minimum tap changing operations. OLTC can be used in rather different control mechanisms distinguished by constant set point curve irrespective of the voltage variation, partly linear voltage set point curve, completely linear curve and linear voltage set point curve with the hysteresis band. All other mechanism without hysteresis have a high count of tap changing operation that leads to the wearing and requires frequent repairs [4].

In the long radial systems, the limitations on OLTC are quite clear; they will not be able to keep the voltage within limits because of the limited tap steps and the sluggish response which leads to violations. Some schemes related to Static Compensators (STATCOM) on the load side with the OLTC operations are proposed in [5] that are able to keep the voltage within specific range. OLTC is the main controlling device but until it operates, STATCOM provides the necessary reactive power compensation with the rapid response to circumvent the voltage violation.

2.2.2 Shunt Capacitor Banks (SCB)

SCB is conventional equipment that is effectively used in the voltage control paradigm in passive networks. Its main function is to keep the power factor value close to unity. Mainly, it has to provide the excess amount of reactive power required in the large loading conditions and to reduce the losses in the system. Nevertheless, the exponential increase of DG units will mark the limitations of its usage- A source with both inductive and capacitive capabilities is required to fully mitigate the voltage value problem. It causes an increase in losses and reduction in the loading capacity of the network. Moreover, due to the resistance dominant nature of the distribution system, it is not considered to be the most effective in DG penetrated systems alone, while being quite effective in passive network voltage control strategies.

Capacitor bank size and values of the capacitors to be used depend upon the loading of the system. As the load curve of the system is not constant, variable and fixed capacitors are used in one module. Fixed capacitors are always switched on because their values are corresponding to the base load, while, variable ones are only used in the overloading condition. Thereafter, the positioning of the capacitor in the system also plays an important role. They can be placed in the substation as well as on the loading side. Still, the voltage value optimality is different for various locations in the whole system. Different methods for the optimal location of SCB are proposed in [6]. Namely, they are Analytical, Numerical Programming, Heuristic and Artificial Intelligence Methods.

The analytical method is concerned with the algorithms that make assumptions based on the sensitivity of constraints to the positioning of SCB. Many constraints are neglected that are considered having minor effect on the final results. Numerical programming is an iterative method that maximizes the objective function to get the desired results. In the heuristic method, clues, proposals or rule of thumb based methods are used that are developed by instinctive thinking and experience. Artificial intelligence is considered the subtype of heuristic methods.

2.2.3 SVRs and SVCs

SVR are autotransformers which are mounted with a sensing device which is capable of monitoring the voltage of the distribution system. It can be placed in the substation or downstream in the distribution network. LDC mechanism with SVR emerges as a suitable framework for the optimal voltage control. For the voltage drop calculation current transformer are used, which measure the feeder current and the impedance settings of the LDC which are kept as close as possible to the original values. During violations, they are capable of keeping the voltage at the integration point equal to the nominal value after the dead band of a few seconds.

Current and potential transformers measure the parameters of the line and change the output of the regulator to the value which will eradicate the voltage value problem. Relationship between V_S and V_L , supply voltage and load voltage respectively, can be signified by the equation:

$$V_S = \frac{V_L}{n_R} \tag{1}$$

Where "n_R" is the transformation ratio which is dependent upon the regulation mode of SVR.

In contrast to SVR, SVC takes complete advantage of the power electronics technology for the elimination of voltage fluctuations, flicker and maintaining regulated voltage in the distribution system. SVC is incurred preference over SVR, because of its brusque control reaction removing the abnormalities in the voltage profile. Based on their control mechanism, SVCs can be categorized into two types:

Self-commutated SVC has accessories that are capable of voltage control, utilizing switched values, as in case of Gate Turn-Off thyristors (GTOs).

Externally-commutated SVCs use Thyristor Controlled Reactors (TCR) for system voltage stability. Thyristor's control signals can be controlled externally depending upon the situation. Its reaction speed and unwanted harmonic influx in the system are the deciding characteristics for its area of usage.

Types of SVC and its reactive power support graph for voltage are shown in the following Figure 1:

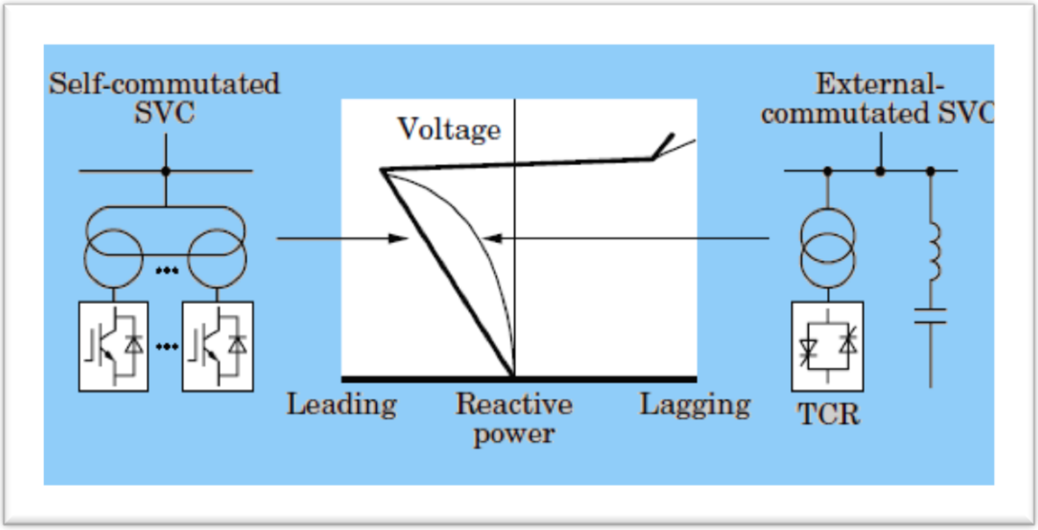

Figure 1 Types of SVCs and respective voltage support characteristic curves

2.2.4 Distributed Generation (DG)

Power production is moving towards the cleaner and nature friendly resources; DG integration is becoming quite common within distribution systems. DG has influence on the voltage profile and network protection structure. As the voltage sags and swells are induced by intermittent DGs, the system is more vulnerable to false trips. Fault levels of the network are also increased due to the infiltration of DG in the system.

Voltage drop across the distribution feeder can be theoretically represented by following expression:

$$V_1 - V_2 = \Delta V = \frac{PR + QX}{V_2} \tag{2}$$

The existence of DG, real and reactive power is added into the system that evolves the expression to:

$$V_1 - V_2 = \Delta V = \frac{(P_L - P_{DG})R + (Q_L - (\pm Q_{DG}))X}{V_2} \tag{3}$$

Where P_L, Q_L and P_{DG}, Q_{DG} are the real and reactive power of load and DG respectively. The polarity of Q_{DG} will be determined by its operation mode; absorption or injection mode. During peak hours, with the connection of DG downstream, voltage will remain in the allowable band, but during the off peak hours, voltage at a few nodes will be out of the statutory limit. Figure 2 signifies the Voltage profile changes with the integration of DG in the system.

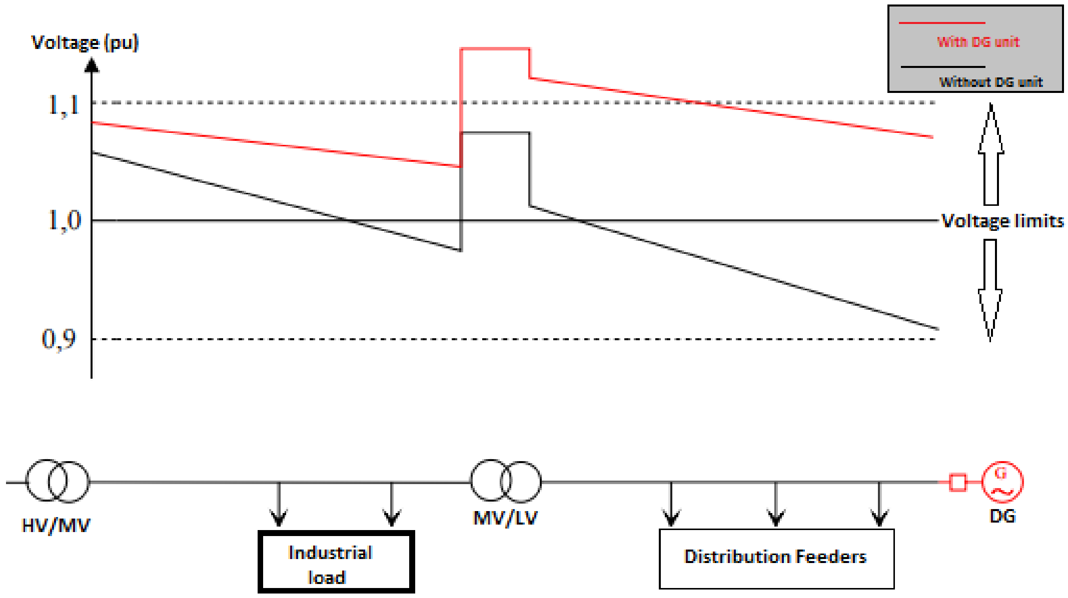

Figure 2 A voltage profile with DG introduction in system

With the ancillary real power support of DG, amount of current drawn from the distribution transformer is reduced. This reduction has great influence on the LDC mechanism that is totally dependent on the current from secondary winding into the feeder. So the working strategy of the voltage control devices that is used in the passive networks should be modified relative to the DG operation. The reduction of current across the transformer will also cause the wrong tap setting of the distribution transformer. DG with intermittent sources like wind, solar etc., also has detrimental effect on the voltage profile. They will cause the hunting problem in the OLTC; taps are changed quite frequently due to the variation of power input.

The methods that can be used to remove the voltage violation at customer premises caused by the integration of DG are:

- New feeder devoted to DG
- Reactive power injection and absorption by DG
- Real power curtailment of DG
- Demand response (load control)
- Storage devices that can be used to remove the high voltage issue

2.2.4.1 Reactive Power Control

DG units can operate as a generator bus where real power and voltage magnitude are specified (for reactive power support by absorption or injection), to provide voltage support. Normally, DNO requires DG to operate at unity power factor or at a constant power factor. They can be operated in Power Factor Control (PFC) mode or in Voltage control (VC) mode. PFC refers to the control that tries to keep reactive power input of DG equal to

the reactive power required by the load, while VC tries to keep the voltage violation problem at bay, irrespective of the amount of reactive power injection or absorption at the integration point. When voltage is within the bandwidth, DG operates in PFC mode, while in violations; the mode reverts to VC mode.

Articles [7] - [10], give the detailed overview of voltage violation eviction with the auxiliary control of DGs. [7] gives the dual mode operation i.e. PFC and VC for voltage magnitude maintenance within statutory limits. This process is usually performed by the power electronic device that is used for the interface between the distribution system and DG. If voltage sensing and processing devices are included in the convertor circuitry, which are capable of sensing the voltage violation and performing necessary calculation for the operation mode change of the convertor, then the voltage violation problem can be mitigated.

Normally, DGs have synchronous machines for power generation, whose reactive power absorption and injection ability can be controlled, reliant on DC excitation current of the field winding as depicted in Figure 3. Depending upon the V-diagram, the power factor of the generator can be tilted from lagging to leading and can be made unity. For voltage rise issue, the generator is set to absorb reactive power and vice versa.

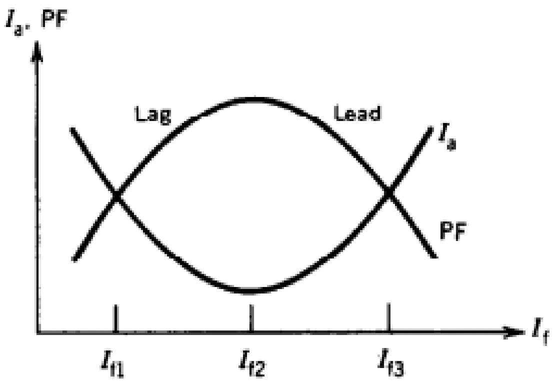

Figure 3 V-diagram of Synchronous Machine

In contrast, if the induction machine is used, then real power and reactive power are interdependent. Such machines cannot be used alone, because they absorb reactive power themselves, but compensating devices like capacitor bank, synchronous condenser or STATCOM should be attached with it [8]. Figure 4 profoundly exhibits the relationship between the real and reactive power of the induction generator in the form of a circle diagram.

Inverter ability likewise assumes an imperative role in the auxiliary voltage support. Mostly PV inverters are not operating at unity PF. They provide the real and reactive power depending upon the PF in day time but the reactive power after sunset is equal to the inverter power rating [9].

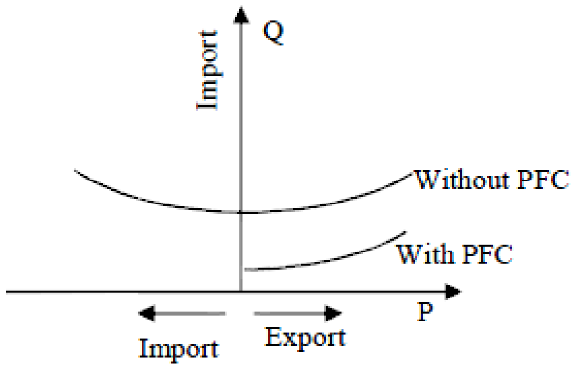

Figure 4 Circle diagram of Induction Machines

The reactive power capability of DG (intermittent) is dependent upon the real power production as the real power provides the check on the maximum reactive power absorption and injection by DG into the system, while the Q-ability of the generator is dependent on the operational limits of the power electronic devices attached between the generator and the grid [43].

$$Q_{max} = \sqrt{S_{max}^2 - P_{avail}^2} \tag{4}$$

Q_{max} , S_{max} and P_{avail} represent the peak reactive power capability of DG, the maximum apparent power of the inverter and the available power from DG at a particular time respectively. The inverter capability curve is shown in Figure 5.

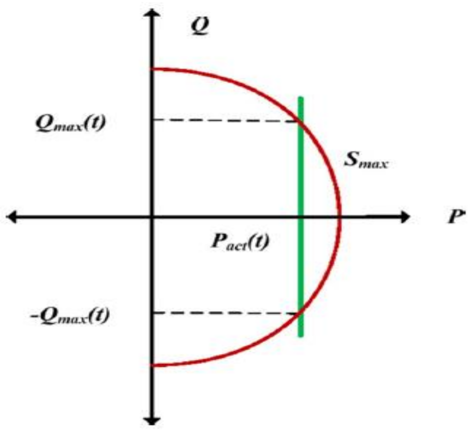

Figure 5 Reactive power capability curve of Inverter [43]

Nonetheless, the optimal positioning of DG fundamentally uproot the voltage drop problem and is able to inject more power without the need of real power curtailment [10].

2.2.4.2 Real power Curtailment

Real power reduction of DGs is not considered as one of the viable choice for voltage control, especially when the percentage of power to be curtailed is high, normally for fiscal reasons. However, as the last resort, DG power can rarely be curtailed. Though, when DG is to be attached in a distribution system, the network should be reinforced with the new line. Otherwise the capacity of the network is used up quite quickly preventing more DG attachments. In such cases, DNO has to address the problem with congestion management that is quite common in transmission systems but cannot be applied in distribution systems, due to lack of information gathering ability. This lacking can be improved by installing sensing and information gathering devices throughout the whole system. The real power reduction of DG will increase the losses that should also be considered while designing curtailment mechanisms.

In case of intermittent resources, the inverters that are associated with them are capable of controlling real power. In Wind turbines, pitch and yaw control are quite beneficial for reducing power in cases of voltage violation. Normally in PVs, maximum power point tracking is used, but the controller can cut short power if required. Similar is the case with small hydro and combined heat and power plants.

In [11], different approaches are analysed, with large number of DGs for curtailment purposes. Firstly, the proportional control is used where the most sensitive generators reduce their generation equally. Secondly, the larger generator is not curtailed; while the smaller one's real power is reduced, with the condition that the generator that is being curtailed should be fiscally supported by the one that is continuously producing power. Lastly, the reduction of real power follows the Euclidean distance; the smallest of the power curtailment of both generators to remove voltage violation. The author of [43] illustrates the P/V droop control for voltage violation eradication. If voltage is increased from the critical value, real power curtailment is employed depending on the droop coefficient. P/V control can be a constant droop or with a certain dead band- The dead band is implied for evading the hunting problem.

Chapter 3

Problem Formulation

3.1 Optimization Objectives

All previously discussed techniques can be utilized for the accomplishment of keeping the voltage within statutory limits. The voltage value should be in the proximity of nominal magnitude of voltage, however, with the control strategy employment, voltage value will settle at the extreme values within limits which require some restoration. At the same time for DNO, the minimization of power loss in the network and real power curtailment of DG is of great significance monetarily. As discussed earlier losses and real power curtailment are interrelated so they should also be considered as objectives to be optimized. In a nut shell, while planning distribution systems with penetrating DGs, objectives that are to be optimized are; power losses minimization, the minimum real power curtailment of DG and minimization of voltage deviation from nominal value.

3.1.1 Voltage Deviation

Voltage deviations from the nominal value at the load nodes or at DG nodes call for an optimized control mechanism. Voltage stability can be referred to the power system's ability to maintain its voltage level within statutory limits, before and after being subject to disturbance. These disturbances are mainly caused by

- OLTC operation
- DG penetration in the system
- Protection equipment operations

Voltage value within the permissible limits is the primary objective to be optimized that is represented by the following expression:

$$f_1(x, y_d, y_c) = \min\ \left(V_i - V_j\right) = \min\ \ (\Delta V) \tag{5}$$

Where V_i & V_j are the sending and receiving ends voltages respectively, while f_1 represents the voltage deviation function from the nominal value. $'x'$ is a dependent variable vector while y_d and y_c are discrete and continuous control variables respectively. In this problem discrete variables can be specified as OLTC and shunt capacitive and reactive devices while continuous variable is real and reactive power capability of DGs.

3.1.2 Power loss

Second factor to be minimized is the power loss that can be modelled by the following expression:

$$f_2(x, y_d, y_c) = \min\ \ (P_{loss}) \tag{6}$$

$$P_{loss} = \sum_{i=1}^{N}\sum_{j=1}^{N} \frac{(V_i - V_j)^2}{R_{ij}} = \sum_{i=1}^{N}\sum_{j=1}^{N} \underline{I}_{ij}^2 \, R_{ij} \tag{7}$$

$$\underline{I}_{ij} = \underline{I}_{p_{ij}} + \underline{I}_{q_{ij}} \tag{8}$$

Where P_{loss} is total real power loss in the distribution system and N is the total number of busses. V_i and V_j are the voltage magnitudes of the nodes i and j, respectively, while R_{ij} is the resistance between these nodes. I_{ij} represents the current in branch connecting i and j nodes. $I_{p_{ij}}$ and $I_{q_{ij}}$ are the currents required for the real and reactive power flow, between the nodes respectively.

3.1.3 DG Real Power Curtailment

DG real power curtailment provides the voltage control but it is not economically efficient. Irrespective of its rarity, real power curtailment minimization will be beneficial for DG owners. The minimization objective can be depicted by the following expression:

$$f_3(x, y_d, y_c) \;=\; \min\; \left(\sum_{i=1}^{N} P_{curt,i}\right) \tag{9}$$

$P_{curt,i}$ is the curtailed active power of i^{th} DG and f_3 is the minimization function of the power to be curtailed for optimal voltage control.

3.2 Operational Constraints

DGs real and reactive power input, the voltage value band of the load bus, the reactive power compensation capability of shunt capacitive devices and tap setting of the transformer are bound by the operational limits of the respective devices. Operational constraints specify these non-volatile boundaries by the following expressions:

$$\begin{cases} T_{min,i} \le T_i \le T_{max,i} \\ Q_{smin,i} \le Q_{s,i} \le Q_{smax,i} \\ Q_{DGmin,i} \le Q_{DG,i} \le Q_{DGmax,i} \\ P_{DGmin,i} \le P_{DG,i} \le P_{DGmax,i} \\ V_{min,i} \le V_i \le V_{max,i} \end{cases} \tag{10}$$

Above expressions depict the boundary limits of the i_{th} OLTC, the shunt capacitive device, the active and reactive power of DG and load bus voltage limitations respectively. For the sake of brevity, all inequality constraints can be lumped up into one simple expression:

$$O(x, y_d, y_c) \le 0 \tag{11}$$

3.3 Problem Statement

From the preceding discussion, it is quite clear that the voltage control paradigm is a multi-objective problem with nonlinear operational constraints. Different optimization techniques and the problem tackling mechanisms will be discussed in the following chapter. However, to adopt a technique for optimization some compact problem statement is required with the clear objectives and limitations of the system that are:

- $f_1(x, y_d, y_c) = \min\ (V_1 - V_2) = \min\ (\Delta V)$
- $f_2(x, y_d, y_c) = \min\ (P_{loss})$
- $f_3\ (x, y_d, y_c) = \ \min\ \left(\sum_{i=1}^{N} P_{curt,i}\ \right)$

Such that

- $O(x, y_d, y_c) \leq 0$

3.3 Problem mitigation techniques

Authors of different publications have utilized various methods reliant on the type and size of the distribution system. If the system is radial and number of controllable devices is small, then rule based algorithms for voltage control are used, while for large and complex systems, this type of approach becomes quite cumbersome. The large number of devices, the increased complexity of distribution networks and sensitive customer devices motivated researchers toward the optimization techniques with extensive computation and precise results. Data utilized in optimization is either measured directly at the nodes or state estimated. So basically the problem of voltage control can be solved by the following techniques:

- Rule based Algorithms
- Optimization Techniques

3.2.1 Rule Based Algorithms

In voltage control, rules that are mostly utilized are relevant to maximum and minimum statutory limits. Substation voltage control is mainly dependent upon loading; if the loading is small, the voltage set point will be turned to the minimum, while maximum loading demands for maximum set point value. The preceding example can be considered as the most simplified rule based algorithm.

In [1] and [12] voltage restoration within limits is attained only by OLTC control which uses the voltage limit violation control rule. Still, it has the limitations of the voltage set points of OLTC, if they already have achieved their extreme settings, then it is not possible to maintain the voltage level within the band. So other controllable entities like DGs reactive and real power and compensation devices should also be considered in control rules. The antecedent problem is removed in [13] and [14] by using the real and reactive power of DGs. Not only the voltage is kept within the limits but also normalized; not remained at very high or low value after voltage violation eradication. Firstly, the basic control is utilized to make the voltage value acceptable and then restoring control is used to bring back the DG operation state close to the state that was before the voltage violation.

In [15], the algorithm used is only utilizing the reactive power capability of DGs while using the sensitivity theory for voltage control. In [11], the author has introduced an algorithm that is capable of voltage control by using the minimum real power curtailment of DG as a control rule. In [5], OLTC and static compensator are used for removing the voltage violation. The main controllability is provided by OLTC yet STATCOM is there for the instant and fast response voltage value restoration. In [4], instead of using voltage on the customer side in control rule, power flow across the transformer is considered the decisive variable. During high input from DER, power flow is negative so the tap of the transformer is changed to the lowest set point and vice versa. Based on fuzzy control rules, the AVC relay is proposed in [16] for voltage control. Fuzzy logic based rules are easy to implement because it only utilizes if and then statements.

3.2.2 Optimization Techniques

As the problem statement signifies the non-linearity of the voltage control problem, different optimization techniques are utilized in various publications. One problem with the rule based approach is its sluggish response that leads towards the need for more robust and sophisticated techniques of optimization using different programming principles and logics based on observations related to evolution. The following figure briefly tells about the different approaches and logics that are being used in the power system related problems.

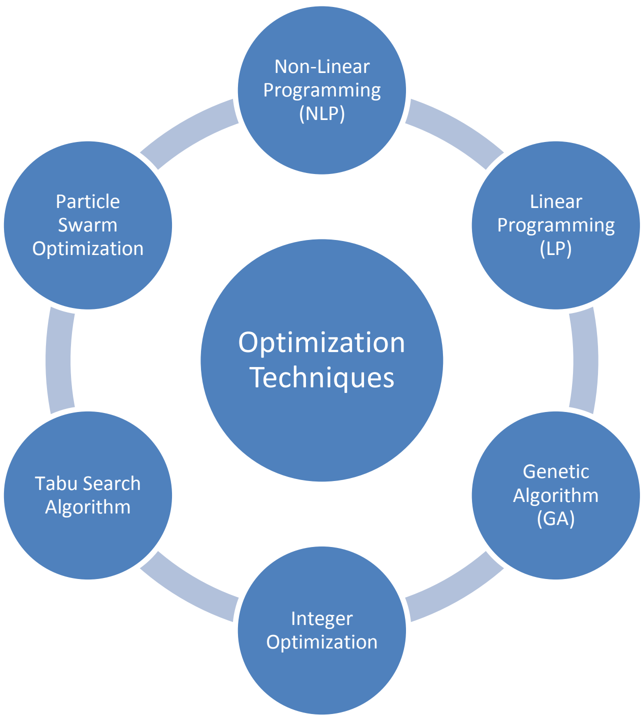

Figure 6 Optimization Techniques

In [14], rule based approach is compared with the optimization algorithm using mixed integer Non-Linear Programming (NLP). Control variables employed are OLTC, shunt capacitors and reactors and DG's active and reactive power capability. In [17], the proposed method uses power loss as objective function and constraints utilized are voltage limits, inverter reactive power capability and OLTC operation. The genetic algorithm is utilized, which is made for optimization problems inspired from the evolution of living organisms. [3] proposes integer optimization technique for the calculation of OLTC values and errors in the voltage value at the load bus. The Tabu search algorithm is used for optimal control action determination in [18]. Other optimization techniques proposed by different authors are the particle swam optimization, linear programming (LP) and integer optimization.

One of the drawbacks of LP and NLP is that it takes all the control variables as continuous. However, this is not the case in the real system. So another technique is required to assign discrete variables instead of continuous ones. The fundamental problem related to all optimization techniques is convergence. If by any chance, the data gathered is wrong, or the algorithm synthesized is an open loop, then irrespective of the technique employed, the singularity of the control procedure optimization cannot be guaranteed. This scenario would be disastrous if only the optimization technique is utilized for the voltage control. So a hybrid method utilizing both rule based approach and optimization algorithms is recommended for the proper control infrastructure. Moreover, optimization calculations require a lot of computational time if the network is quite complex.

Chapter 4

Voltage Management Practices

4.1 Voltage Control Architectures

Traditionally, voltage control by utilizing OLTC relying on load forecasting was a good method for passive systems. With the introduction of DGs, distribution systems have advanced towards active system that requires new control architectures ranging from the control of OLTC from the centralized command centre to the vicinity of the controllable devices like DGs and SVCs.

Based on methods that are published, voltage control architecture can be divided into three main categories, from which one is further divided into two sub categories as depicted in Figure 7.

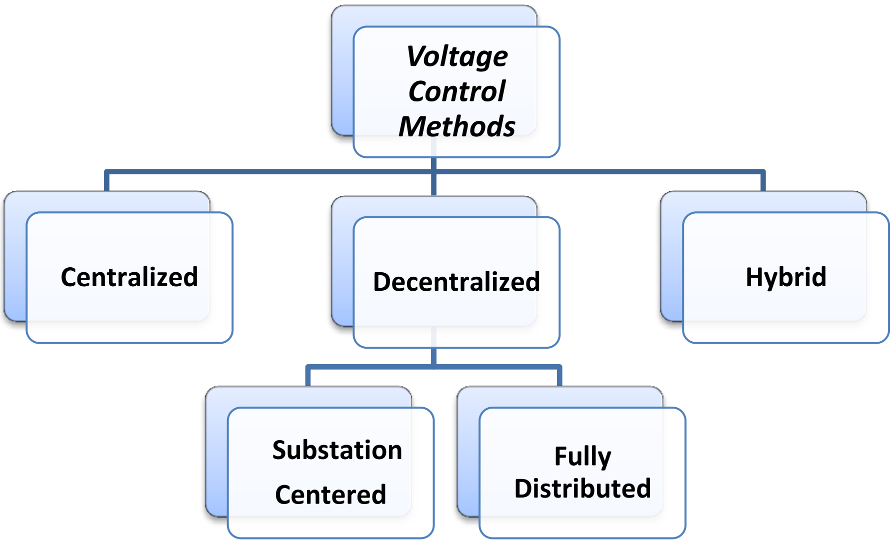

Figure 7 Voltage Control Methods

4.1.1 Centralized Method

In a centralized architecture, decision making and control actions are made by the central control facility far away from the equipment that is being controlled. Mainly, substation data from all distribution substations is gathered at a centralized facility and all the computations and logical conclusions for voltage control strategy are made at that focal point. Limitation that marks this architecture is the communication system that requires being fast and should not be limited by the data transfer capability. This control architecture which requires data input from all the sensors in the distribution system, illustrates the need for wide measurements along the distribution architecture such as WAMS. A complete control strategy is determined using extensive optimization algorithms. Optimum utilization and complete co-ordination between the controllable entities are the main attributes of this architecture. This architecture does not take any action without the consent of the operator.

In [2], [3], [16] and [17] centralized OLTC control is proposed with different optimization techniques. Method proposed in [2] uses OLTC, aided with line drop compensation for voltage control named Automatic Compensation Voltage Control (ACVC). [3] further enhances the LDC method to Multi-Line Drop Compensation (MLDC) that utilizes diversified load data and power input from DG for proper voltage control with OLTC. Method proposed in [16] makes OLTC control more potent by removing the only side effect of LDC; the reference values of LDC have to be changed with the changing load. Fuzzy logic based AVC relay is proposed which is independent of the loading conditions. Lastly, in [17], OLTC is controlled in co-ordination with DGs reactive power control to maintain voltage value within statutory limits.

[4] depicts a method that is capable of voltage control only by changing the OLTC set points. The method used is capable of utilizing the idea of power flow across the tap changer. [18] only used Static VAR Compensator (SVC) for voltage control. In [12-14], co-ordinated Voltage Control (CVC) methods are proposed that are able to perform basic and restoring control dependent on the control rule for voltage fluctuation removal. Actors involved are DG units and OLTC. Lastly, the innovative controllability of Smart Transformer (ST) is used for controlling the voltage fluctuations in every phase individually, based on the state optimization method in [20].

4.1.2 Decentralized Method

This design is mainly associated with voltage control outside of the central control system. This can be done by the local substation or at the nodes where loads are attached. This architecture generally utilizes minimum amount of data and coordination between the adjoining nodes and the substation. So, this framework is least vulnerable to communication hazards. This method is further divided into [19]:

- Substation centred control
- Fully distributed control

Substation centred control utilizes the logics of voltage control that reside at the local substation, capable of controlling various feeders having limited coordination with the remote command unit. If more powerful distribution control software is used, it is possible to control feeders that are under the jurisdiction of other substations.

The fully distributed system utilizes the control units that are deployed in the vicinity of control equipment. Control units are capable of making decision with the limited amount of data available and least amount of coordination with the substation or adjacent nodes. These intelligence devices are equipped with required logics and optimization techniques that can perform the problem befitted control decisions. This type of mechanism does not require strong communication infrastructure because it is rarely used. In this architecture it is obligatory to notify the operator of every action but the control action validity by the operator is optional.

Different approaches of decentralized control are proposed by the authors of [7], [11], [21] and [22] that use actors like OLTC, Load Ratio Transfer (LRT), SVC, SVR and DG, utilizing different optimization techniques. A fully distributed control method is proposed by the author of [22] that uses the Feed Forward Neural Network (FFNN) as controller. GA is used for generating data of the system for the training of FFNN a day ahead of control schedule. Actors involved in the proposed method are LRT, SVC and SVR. The author of [21] proposed a method that shifted the mechanism towards substation centred architecture. Actors; OLTC, substation and feeder capacitors are controlled by pre-determined set points that are calculated from the load forecasting and offline simulations. Fully distributed control can easily be managed by the control of DGs. [7] proposes the dual mode control method that is capable of operating a DG in PFC and VC modes. This method also has the capacity to use active power curtailment as the last resort. If active power curtailment has to be used, [11] proposed a method of curtailment based on the sensitivity matrix obtained from load flow analysis. This particular method ensures that DG has minimum production curtailment and the one that is curtailed if fully compensated fiscally.

As the distribution system is becoming complex day by day, fully distributed systems are being more thoroughly researched. Agent is a new paradigm which has made the system fully decentralized with the magnificent advantages of robustness and minimum communication between nodes and substation. Agents are further used in chunks with proper coordination that give rise to Multi-Agent System (MAS), that are capable of achieving goals which are impossible for a single agent. This concept is critically explained in the next chapter.

4.1.3 Hybrid Method

This method is capable of using the pros of both centralized and decentralized infrastructures indifference of the respective cons. This method is referred to as the balanced approach to the distribution system. The centralized system is vulnerable to single point failure and the decentralized system can give rise to the control procedures that might not be optimal due to the limitations of acquiring and processing data, so the hybrid method is useful in such irregularities. Some control action require DNO’s approval while for some actions, it can proceed with some actions without the acceptance of the operator.

[5], [21] and [23] recommended hybrid control for voltage violations. OLTC and STATCOM are controlled based on the artificial neural network concept in [5]. Local voltage control is provided by STATCOM that is marked by its robust support, assisted by an OLTC. The remote control of OLTC, substation capacitors and the feeder capacitors based on load forecasting is proposed in [21]. DG’s controllability by Distribution Management System (DMS) and supervisory control by Energy Management System (EMS) is proposed in [23]. The proposed scheme uses local control based on DMS, when all the operational constraints of the system are being conformed. If some DGs are not able to meet the working constraints in the proposed control scheme, the procedure proposed is forwarded to EMS for authentication. As long as it is supported by EMS, the control procedure is sent to the controllable actors. Contrarily, if the devised scheme is rejected new control scheme is scheduled by DMS.

4.1.4 Method Selection Criteria

All the methods that are discussed previously are capable of voltage control quite accurately. As described by the author of [19], different deciding factors for the best suited architecture as a control scheme are:

- Security
- Speed
- Complexity

Security signifies the safety level of the assets of the customers that should be fulfilled in any hazardous situation. Speed refers to the maximum allowable latency for the voltage to stay out of the allowable band. Complexity connotes the amount of changes required in the system for the voltage control application. All antecedent criteria are quite beneficial in choosing the best voltage control infrastructure. Speed and complexity will mark the use of different architectures with different system situation. Systems where low latency is obliged should be adapted with distributed infrastructure, which requires least amount of communication and processing overhead. Depending on the complexity, latency can vary from microseconds to milliseconds. Generally, the system that are more complex needs the centralized control methods to cope with frequent system structure changes and to keep the coherence of the system architecture with the model specified. Figure 8 below signifies the speed of different architectures with varying complexity.

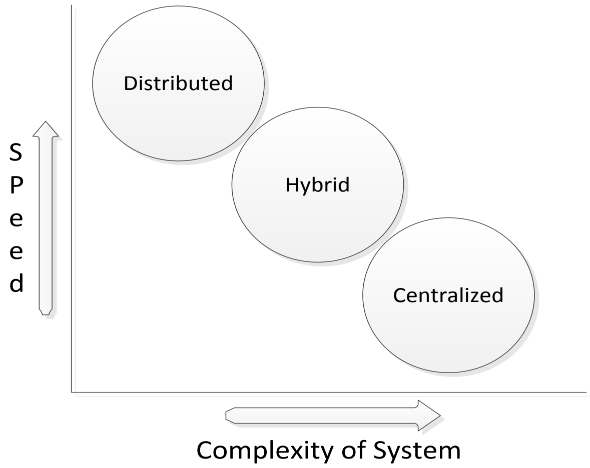

Figure 8 Complexity vs Speed graph for various voltage control schemes

Other than speed, security and complexity there are other factors that have an impact on the selection yardstick; the number of feeders that are going to be automated, operator awareness of the system state, communication devices, amount of data to be processed and the accessibility of products for a specific control mechanism [19]. DNO also has to think constructively while specifying a budget for a particular architecture, because the quality of the control equipment and processing units depends upon it.

4.1.5 Summary of voltage control methods

Figure 9 summarizes different methods, communication trends and specific positions where the control logic resides. Centralized logic has the knowledge of different substations and it acts as a focal point in the control hierarchy. Substation centred control only has communication with the downstream actors of the distribution system, mostly with feeders and DG units. Finally, the fully distributed control takes actions on the nodes, while having the knowledge of adjacent nodes and DG units is enough for control decision deduction and updating the control device set points.

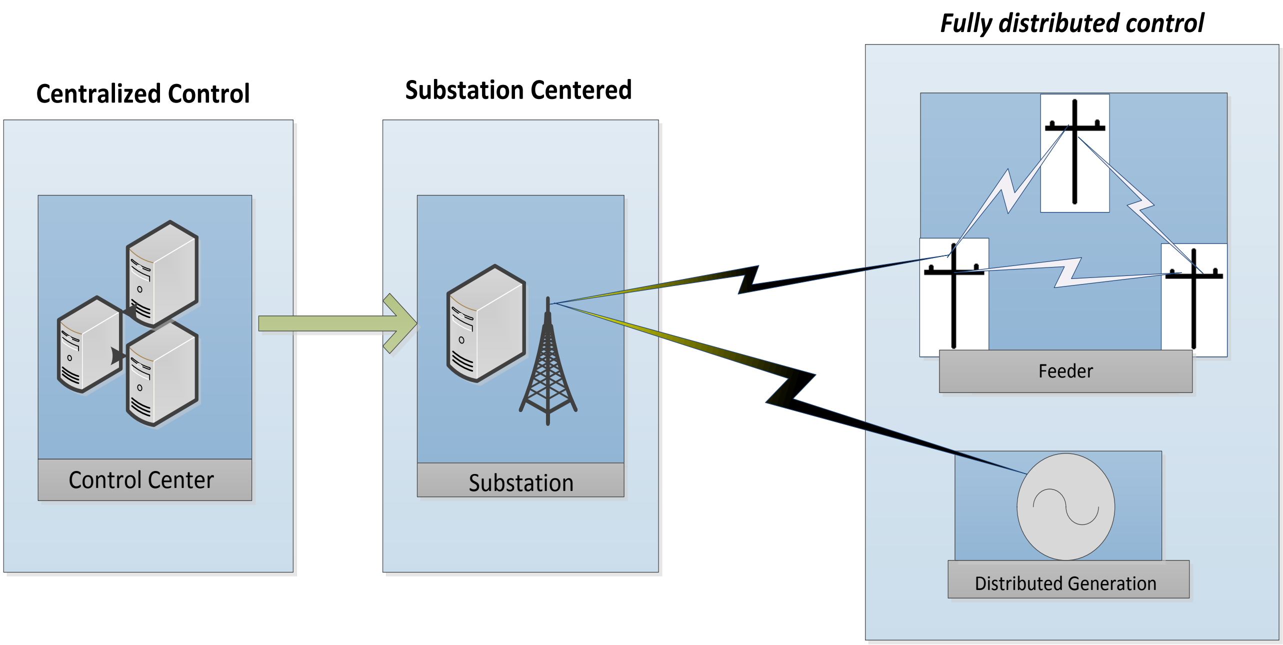

Figure 9 Voltage Control Methods and their Control Centres

4.2 Agent Based Systems

This thesis is going to propose a voltage control method based on the very idea of agents, which are able to make decision autonomously and in coordination with other agents to make the objective realizable. As discussed above agents are mainly related with the fully distributed architecture; some basics of intelligent agents, their environment and their media of communication needs to be discussed here.

4.2.1 Agents

In a broader aspect, any controlling entity can be considered as an agent that presents the specific degree of autonomy such as the thermostat. More specifically:

"An agent can be software or a hardware that is capable of making decisions autonomously depending upon the objective to be fulfilled, when placed in an environment."

Autonomous behaviour refers to the control that is being performed without Human Machine Interference and is based on the observed data of the environment. As for environment, it can be anything outside agent's boundary; it can be physical or a virtual environment. Environment can be divided into following types [24]:

- ***Accessible:*** one where information obtained through sensors is precise and progressive.
- ***Deterministic:*** one where the state of the environment assumed is unmistakeably correct.
- ***Episodic:*** one where the control actions of the agent are related to the current state, independent of the past one.
- ***Static:*** one where the state of the environment is the same, until or unless the agent takes some definitive action to fulfil its targets.
- ***Discrete:*** one where number of moves that can be contrived by the agents are discrete.

The agent's association with environment and the respective communication signals are depicted in the basic block diagram shown in Figure10:

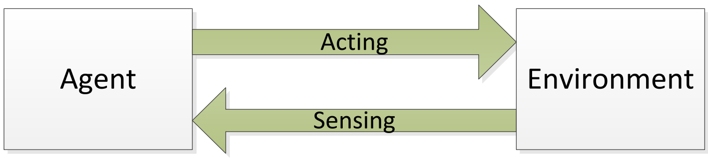

Figure 10 Basic Interaction between agent and its environment

The agent is not able to control the whole environment. Furthermore, each agent has a predefined objective that remains the same irrespective of the environment in which they are implanted. If the same agent is placed in different environments, it will depict diverse actions relying upon the sensors data availability to fulfil the same goal that is hardwired into it. The simple examples of agents are relays (physical agents), that are capable of responding to environment changes through physical means, and virus checkers (software agents), capable of removing malicious software from any computing device.

4.2.2 Intelligent Agents

Any system capable of voluntary actions can be assumed as an agent. The multi agent system comprises agents that are able to fuse the concept of flexibility with autonomy. So intrinsically, intelligence is correlated to the degree of flexibility presented by the agent to complete its predefined task. Flexibility can be thoroughly examined by the following three qualities [24]:

- ***Reactivity:*** Ability of an agent to take a certain action, reliant on changes in environment, to fulfil the goal with minimum latency.
- ***Pro-activeness:*** depiction of goal driven attitudes; necessary steps are taken to fulfil the task that is assigned. Pro-activeness can also be referred to the inventiveness of the agent.
- ***Social ability:*** Agent specific ability to interact with adjacent agents to achieve goals.

The reactive agent and the goal driven agent are converse to each other. Agents that are able to react to any environmental change are easy to fabricate, other than the agents whose reaction is directed towards the achievement of goal and environment stabilization, both at the same instant. Social ability signifies the negotiation and cooperation between the agents for fulfilment of the task. This particular communication is assisted by Agent Communication Language (ACL), which let the agent's converse rather than simple passage of information.

Primarily, the intelligent agent consists of four fundamental components [41]: the input channel, the output channel, decision making block and communication system. Sensors are able to monitor changes in the system that is stored in the memory block after successful detection. Stored data is utilized for processing, based on some optimization algorithm. Finally, the communication interface is a must for completing the intelligent agent architecture. The generic model of the intelligent agent is portrayed in Figure 11.

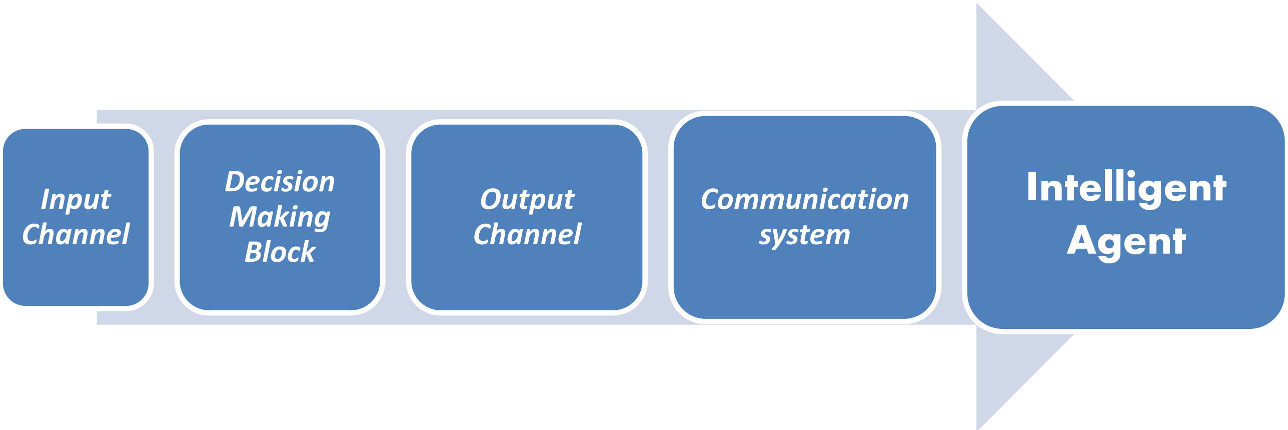

Figure 11 Intelligent Agent Model

4.2.3 Architecture for Intelligent Agents

Architecture actually gives the inner map of the agent, data structures inside the agent and actions that are to be performed on those structures for autonomous control. Agents can be designed based on different architectures. Some use only the abstract ideas while others are based on solid reasoning that is related to task and environment suitability. They can be classified into two basic architectures and each has further subdivisions [24]:

- Abstract architectures
- Concrete architectures

4.2.3.1 Abstract Architecture

Based on the antecedent discussion, an abstract architecture is:

"Representation of an agent, by an action function that is capable of bringing changes to the environment, without any elucidated logic and control strategy."

This architecture is just an abstract which mainly assumes the environment states where the agent has to act and define them, while agents respond to these different environment states with action function. The agent somehow deduces the action to be performed, without any well-defined decision making framework. On the basis of agent's ability, this architecture can be further divided into the following types:

- ***Purely reactive agent:*** Architecture that does not take past actions into account and act totally dependent upon the coeval environmental changes.

- ***Perceptive agent:*** Agent's structure is divided into two subsystems; perception and action subsystems.
- ***The agent with states:*** This architecture utilizes a part of data structures to store the previous states of environment and actions are based on the sequence of these precedent states.

4.2.3.2 Concrete Architecture

Abstract architecture's inability to define the decision making block of the agent leads to the concrete architecture that is:

"Depiction of an agent with the well-defined decision-making block; based on predefined rules and algorithms, which are established over solid reasoning. "

Dependent on the reasoning based approach, concrete architecture further divides the agents into following four types:

- ***Logic based agents:*** in which decision making is based on some solid logic.
- ***Reactive agents:*** Direct mapping between the environmental situation and action to be performed, is done to reach an efficient decision.
- ***Belief-desire-intention agents:*** where the decision is made through fitting coordination between the belief, desire and the intention data structures of the agent. The belief block determines whether the changes observed are under agent's jurisdiction or not. If they are, then the desire block specifies the outcome that ought to be the result after agent actions. Finally, the intention block will specify the set of actions that will be convenient in adapting with environmental change.
- ***Layered architecture:*** where the decision making block is fabricated in layers and each has the reasoning based approach to reach the final result in consensus with all the other layers. Basic layers in this architecture are the message handling layer, the behavioural layer and the functional layer [26].

4.2.4 Multi-Agent System

"System consisting of more than one intelligent agent accomplishes Multi-Agent System (MAS). "

It ought to be cleared that whole system does not have a single goal, but each local agent has their own goals to fulfil. More typically, a complex task that is to be performed by a single agent is distributed among different agents in the form of various straight forward tasks. Definition of agency that is implied signifies the communicating ability of the MAS; they can be considered communicating with each other or can be deemed as non-conversing. So more sophisticated definition is:

"MAS consist of collection of various agents, bounded by an environment which are conversing with each other through the proper communication channel (more specifically a language), for the purpose of achieving agent respective goals."

Generic MAS ought to have at least following attributes which also justify their use in various applications [25]:

- Autonomy
- Flexibility
- Extensibility
- Open architecture
- Fault tolerance

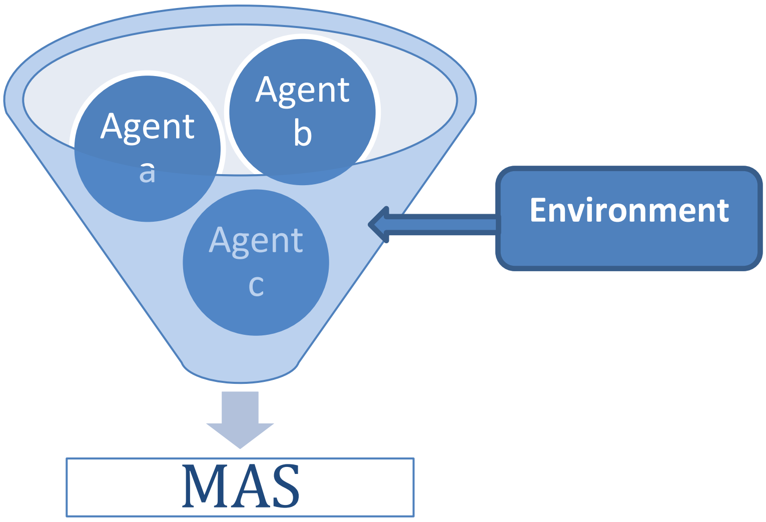

Figure 12 Generic MAS Model

With agents as the building block, the autonomy of MAS is for granted. Large numbers of co-operation requests are taken in by each of the agents by the adjoining ones, as they have authorization to choose from different tasks or to neglect them based on their priority proclaims their autonomous behaviour. Flexibility refers to the legitimate response to the varying environmental stimulus. It also insinuates that the agent should have a large number of actions on inventory, from which it can choose, to tackle the varying responses robustly. There should also be room for improvement in good MAS that makes the system extensible. True extensibility refers to the addition of a new trait without making any changes in the existing setup, operation and structure of the agents muddled in MAS.

Earlier, closed architecture was in use which has certain limitation; no new agent can be added to the system and if by any means it is included in the running system, other agents remain unaware of its presence. Nowadays, MAS is designed as an open architecture that gives rise to many constructive possibilities. The main trait that signifies the importance of an open architecture is that no particular language is designated for the development of an agent. While some standards related to agent communication are exercised by Foundation of Intelligent and Physical Agents (FIPA) that makes location, creation and the removal of an agent, a smooth process. There is a

FIPA agent reference model that can generally be referred to as an agent platform. Model main utilities are [26]:

- Agent Management Service agent (AMS)
- Directory facilitator (DF)

Presence of AMS in an agent platform is obligatory while DF is optional. AMS not only keeps track of the agents that are in MAS, but also keeps information about their names and lifecycle tenure. Other Agent alluded as DF is able to provide information about the availability and tasks of all the agents embodied in the system. Interoperability between various agent platforms is one of the significant features of FIPA model. Figure 13 depicts the FIPA model of MAS.

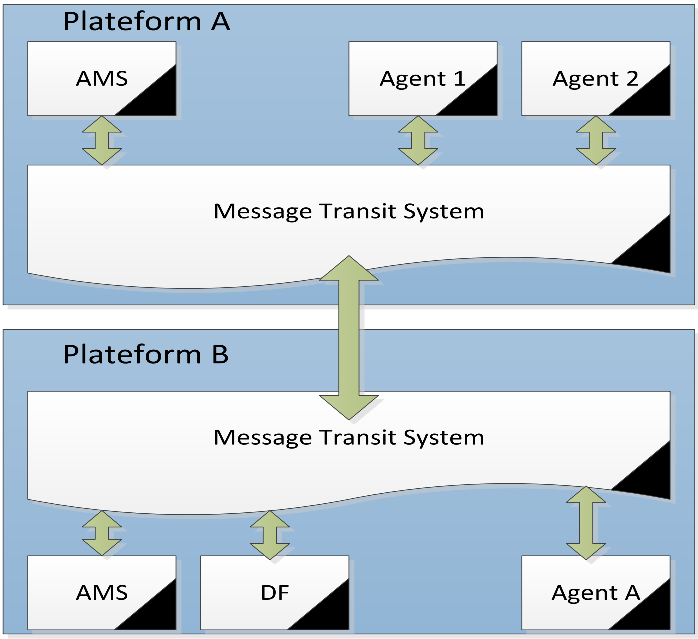

Figure [13] FIPA Model of MAS

The fault tolerance of MAS refers to the system's ability to reach desired results, irrespective of occurrence of faults. The fault can be linked with the hardware or software functionality of agents. Hardware related problems can be eradicated by providing redundant agents, while the software problems need agents to take desired action with the implementation of different logics from the previous ones. In the worst case scenario, the system should be able to achieve the results as much as it can without keeping the whole system as leverage.

4.2.5 Communication layers in MAS

As discussed previously, agents can only be reactive or intelligence can also be included. The intelligent agent can also be referred to the cognitive agent that has the properties of autonomy, decision making and conversing with various agents. Relying on location and amount of knowledge that is to be processed and interpreted, MAS can have three layers [41] which are:

- ***Reactive layer*** primarily consist of cognitive agents that counter environmental stimulus while only depending upon the data that is confined to a particular subsystem. For instance, agents that are related to self-healing actions on the smart grid constitute the reactive layer.

- ***Co-ordination layer***, mainly monitor the action of agents in MAS based on priorities and take actions if the priority of the agent is neglected due to some anomaly. Moreover, co-ordination layer act as a bridge between the reactive and deliberative layer by interpreting the action of the reactive layer to the higher ups, as it keeps the complete log of action that took place in the reactive layer. This layer also deciphers the control signals for the downstream layer which is coming from higher up in the hierarchy.
- ***Deliberate layer***, is on top in the hierarchy and responsible for generating commands to keep the whole MAS system consistent. It widely monitors the whole system under its jurisdiction and makes plans for a longer period of time, in contrast to the reactive layer that makes decisions for its subsystem only for the short interval.

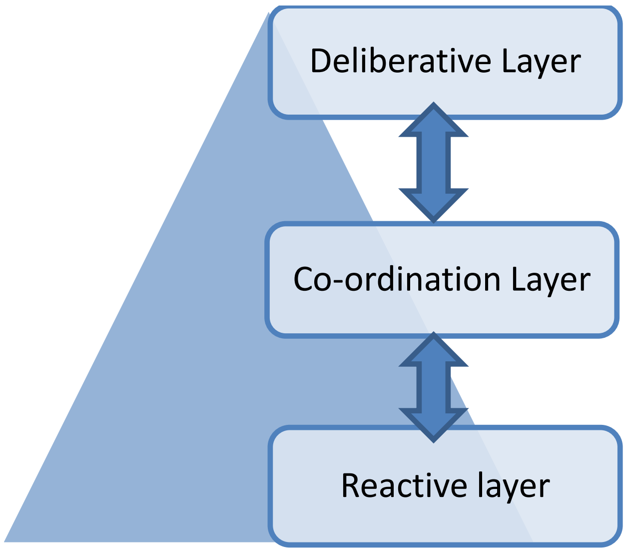

Figure 14 Layers in MAS

4.2.6 Applications of MAS

MAS can be utilized as an innovative solution for the power engineering related issues. Different authors have discussed various scope areas of its applications who point out some main features of the fields of implementation. Briefly, the system should have following characteristics [25]:

- Consist of several subsystems.
- Has a large number of control entities and communication between them is obligatory in regular intervals.
- Large amount of data is available and its processing without intervention from central control is required.
- The addition of new features or extending some existing ones, in the original planning of the system is required.

Based on the above discussed scenarios, the power engineering applications of MAS can be narrowed down to following four categories [25]:

1. Monitoring and diagnostics is fairly researched for MAS based Operations. One of the key features of agents is its ability to monitor the environment and derive diagnostics dependent upon observations that can be utilized in condition monitoring of the electrical equipment and diagnostics of faults in the power system. Firstly, the data is gathered and interpreted, that leads to organising and processing, which can be used for diagnostics and stabilizing the system by altering faulty entities.
2. Protection is the least touched area of power engineering, by MAS architectures. Nevertheless, research is being conducted to utilize agents and protection equipment in correlation, which will expedite fault tolerance and self-healing networks.
3. Modelling is mainly related to the software technologies and complex system tasks, in which the complex goal requires to be divided into various auxiliary projects, which are to be completed by task specific agents.
4. Distributed control is booming in the distribution system, utilising MAS. With the increasing number of DGs and energy market liberalization, there is a need for local control that gives rise to effective decentralised decision making in network alteration and DGs active and reactive power control.

4.2.7 Types of MAS

Briefly discussed applications and the communication attitude of different agents in MAS are the perfect base for the division of MAS into different organizational structures. Broadly, they can be divided into three different types that are [27]:

- Hierarchical MAS
- Flat MAS
- Modular MAS

4.2.7.1 Hierarchical MAS

This structure strongly restricts the communication of agents in the predefined boundaries of the hierarchy. This behaviour makes the system less autonomous that is not a viable option for distributed structures. Furthermore, the segregation of the system into higher and lower level agents makes the agents interdependent, while the upper level agents have the capability to partially or fully control the lower level ones. This hierarchical control attitude makes the system suitable for centralized structures. At the other end of the spectrum, this structure reduces the communication between agents to the minimum and need for DF is eliminated. Agents that are higher up in the hierarchy are responsible for the location of the lower agents, for the realization of their goals.

The subsumption organization of MAS can be considered as the subtype of the hierarchical system. In this system, building blocks of agents are also agents of the system, which require the complete subsuming of building block agents by the one in command. Relying on their behaviour, they can be named as the container agent and the subsumed agent. This property restricts the system to predefined tasks that are hardwired into it during its creation, with minimum innovation in task management. Moreover, it makes the system non extensible and virtually the least flexible one. Figure 15 gives the rough sketch of the hierarchical infrastructure of MAS.

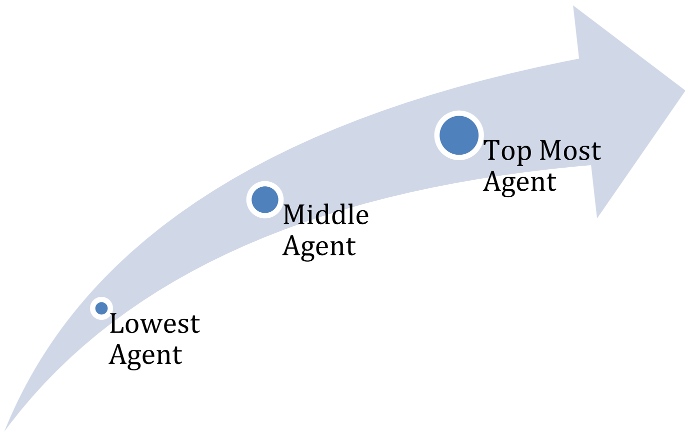

Figure 15 Hierarchical MAS

Authors of [28]-[32] publications gave different description for the usage of hierarchical architecture. [28] and [29] uses this architecture in centralised manner. Method proposed in [28] gain voltage stability from the reactive power control of DGs. Agents utilised are the feeder relay, the top feeder relay and the controller relay. While method of [29] utilizes the Distribution Transformer (DT) agent as a primary voltage control entity. DG control is initialized if primary control does not have satisfactory results and real power curtailment is used as the last resort. The method proposed uses Parent child methodology based on spanning tree theory.

As the distribution system is advancing towards decentralised control, [30] and [31] depicts the distributed control utilizing upper agent (Management agent) and several lower agents (local agents). Voltage control of [30] is based on OLTC that utilizes the control rules based on the minimization of tap changer operation for voltage control from the economic point of view while [31] uses the voltage deviation matrix and voltage/sensitivity as optimization constraints. Antecedent methods discussed are substation centred, while fully distributed control requires agent placement at each load node. [32] gives the insight of hierarchical MAS concept by using bus agents, defined at every bus, that are adept at controlling voltage by co-ordinating with OLTC and DERs.

4.2.7.2 Flat MAS

In contrast to hierarchical organization, the flat system does not imply the restriction of control, relied upon the rank in the hierarchy. Moreover, each agent in the system is capable of communicating with other agents, to dynamically achieve their goals and change control actions instinctively with the changing network control requirements. This makes the system a perfect match for the distributed control applications. Though, this system requires the information of all the agents beforehand, but it does not affect the robustness and openness of the MAS architecture. DF is an important entity of this system, as it provides an impeccable platform for agents to select actors (other agents), which are perfect for a certain task. Figure 16 gives some idea about Flat MAS.

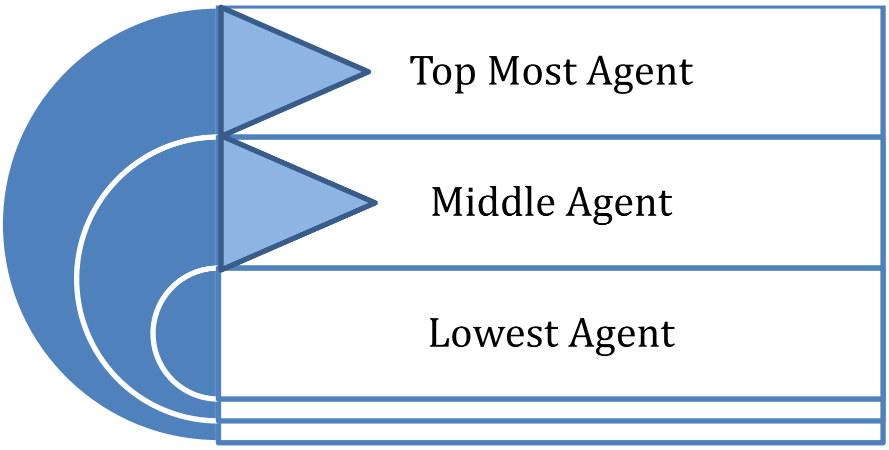

Figure 16 Flat MAS

In [33]-[37], different flat MAS architectures are proposed. In [33], this architecture is utilised as a partly centralized one in [33]. Fuzzy rule based control is employed for control optimization using OLTC, DG and load agents. OLTC and DG are the control agents while load agent is only exploited as the voltage monitoring entity.

In [34] only shunt control devices are utilized, by using execution and co-ordination agents, and the heuristic method for optimal control calculations is proposed, while [35] exploits DG reactive power control with the help of the agent at each DG node. Agents exploited in the latter article, can be operated in any of the self, compensation and broker behaviour. Self-behaviour is utilized for the voltage control of the same bus which is its responsibility, while compensation behaviour provides voltage support in response to call for support from other agents. If the agent is not able to remove the violation of its own bus with available DG support then it acts as a moderator or negotiator and call for voltage support from other DG node agents. The precedent methods are not able to remove violation in one go, but require the number of iterations to bring back voltage within permissible limits.

The method proposed in [36] does not require iterations that were the issue with the former methods. The bus, service and load flow agents are utilized based on DF records. Bus agents are monitoring their respective buses and removing the violations with the help from service agents that act as moderators. Load flow agents have calculated the load flow results of the system, which are utilized with the reinforcement learning algorithm, for optimal voltage control prediction. All the actors that are required for the complete removal of violation are executed in one go which eradicates the latency problem due to iterations. The dilemma with the proposed method is hunting that arises due to incomplete information about the network, for instance agents do not have the information related to the adjacent nodes.

[37] eradicates the hunting problem by proposing a method that utilizes nodal agents associated with root, branch and leaf nodes. Moreover, it utilises the voltage cost arrays that defines the voltage support economically, from the supportive agents point of view. Nodal agents are able to remove the information lacking problem by giving comprehensive report of the network. Other options that can be employed for this problem are hysteresis control or co-ordination agent utilization. Later method implementation will transform the system into a centralized one.

4.2.7.3 Modular MAS

As the name signifies, this architecture involves the number of modules and each module can be considered as a standalone MAS itself. Within a module system, flexibility, robustness and autonomous control action quality is at the same level as Flat architecture, due to small communication overhead. Conversely, inter modular autonomy is not the same, as the complex re-structuring of the modules and inter module communication are barriers. Zones in the distribution system that are based on the OLTC control of the distribution transformers can be considered as a vague example of a module. Pictorially, Modular MAS is illustrated in Figure 17.

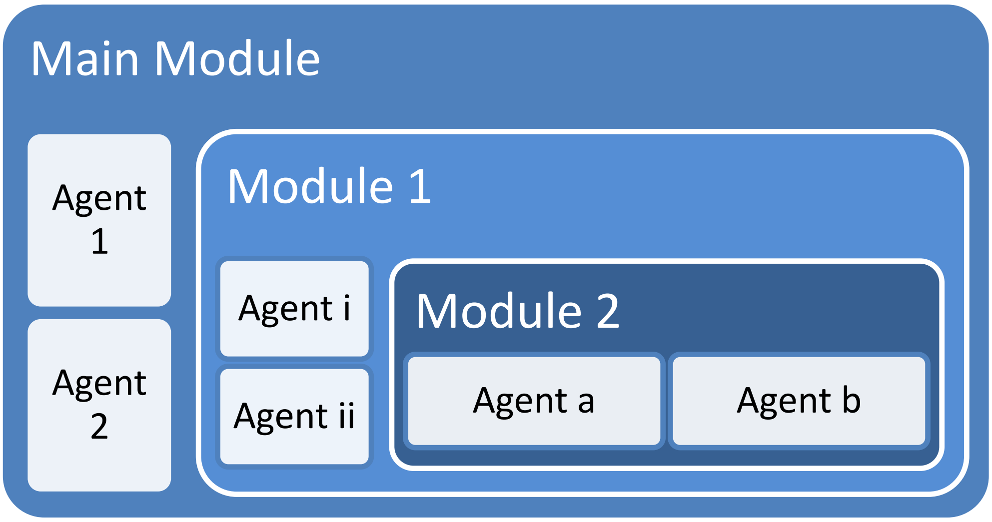

Figure 17 Modular MAS

This architecture is followed for voltage control strategy in publications [38] - [40]. [38] and [39] give the zonal division of the distribution system relying on the electrical distance concept. The proposed methods are examples of the fully distributed system, as there is least amount of communication between adjacent zones. Generator and load agents are employed in the former method while the latter one utilizes agents at DG and shunt devices vicinity.

A cell based approach of modular MAS is depicted in [40]. In the proposed method, feeders are referred to as cells that are capable of total autonomous control based on local controllability. Cell controllability is not restricted to a DG which is also capable of demand side management. OLTC control is utilized, while keeping in mind, that the number of control actions to achieve the goal should be the minimum. If OLTC is not able to control the voltage, then the method relies on cell based control.

Chapter 5

Proposed methodology based on MAS

The goal of this thesis is to give a control architecture that is capable of removing voltage violations without the knowledge of the central control system. For this very purpose of autonomy, agents are utilized in co-ordination with the centralized supervisory control. Voltage violations are mainly removed solely relying on the feeder voltage data and voltage support variables available at that violated point and onwards.

5.1 Generic idea of proposed MAS framework

The suggested scheme of MAS comprises of agents that are fairly distributed in the system to reduce the complexity and dismantling the composite one into different partial systems. Agents are associated with devices that are vital for voltage regulation and at the nodes that are vulnerable to violations. The proposed framework utilizes the flat architecture of agent communication and coordination that makes the system fully automated and distributed. The system consists of:

- OLTC Agent (OLTCA)
- Q-Control Agents (QCA)
- Load Agents (LA)

As the proposed method belongs to flat architecture, therefore communication between agents is not reliant on the hierarchy or modules. Each agent has the respective group of tasks that it has to perform irrespective of other agent's inclusion. OLTCA is a supervisory agent that generates the token at each time step which will move from node to node for voltage violation removal. The token concept is more thoroughly discussed in Section 5.2. At the end of the token contour through the network, it receives the voltage values of each node and the set points of the voltage control variables like SVC and DGs.

Q-control agents are affiliated with any of the reactive power controlling devices that are capable of voltage control by changing its mode of operation i.e., reactive power absorption or injection. SVCs, capacitor banks and DGs are the most prominent reactive power controllable entities that are commonly integrated in the modern distribution system. They modify their set points dependent on the voltage support required. They also keep track of the voltage value of the node whereby it is associated.

Load agents are present at each load node and have the responsibility of measuring the voltage value at each time step, and make decisions based on voltage violation and capability of control devices controlling capability. Technically, however, load nodes are the secondary substations that supply power to the customer premises. When violation occurs, co-ordination between Q-control agents and LA eradicates the problem. Generic depiction of the distribution system with agents and the token transversal in the network is presented in Figure 18:

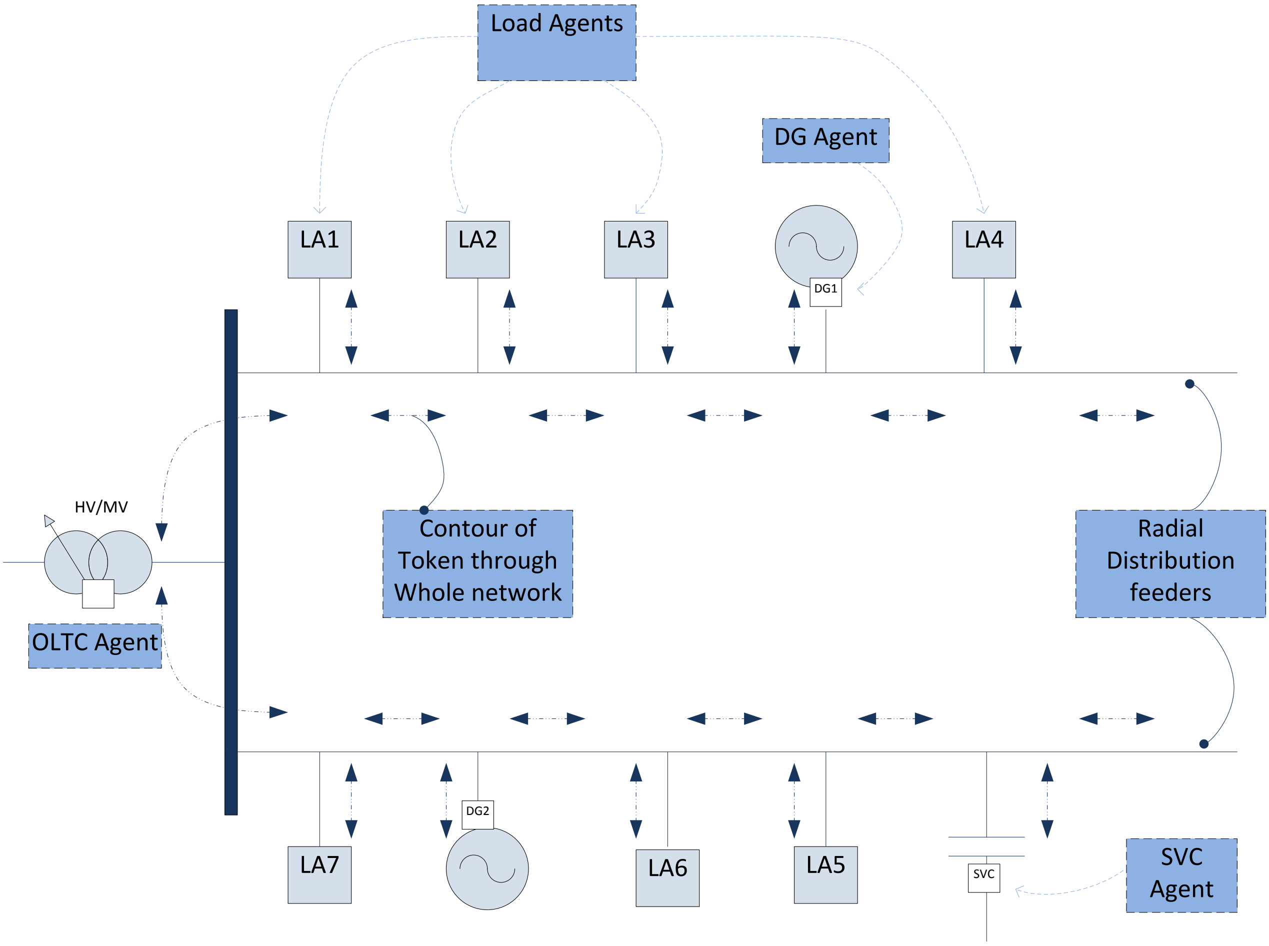

Figure 18 Distribution system with Agents and Token contour path

5.2 Token

Token acts as the main controlling tool in the Distributed Voltage Control (DVC) mechanism proposed. Basically, the token contains the knowledge and permission required to take actions. Not only that, it also has the capability to pass data between the nodes.

The token is generated at each time step from the primary substation. Permission to take action in case of violation, making an inventory of the visited nodes and bringing back sensible data from each node to the primary substation, is hardwired into the token memory. The token has the voltage reference value with which it compares the load agent's measured values and makes a decision reliant on the comparison, whether to have support from the controllers or have the log of the voltage value and move on to the next node. [42] gives the idea of the tuple sequence model for the token representation that is used to represent the token as a four-tuple sequence $< R, F, P, D >$, where R represents the reference value for comparison, F is the function, based on which, the decision about permission grant or refusal is made (voltage statutory limit in this case),

P is the permission for the local control in case of voltage violation and D is the data about the node voltages and the controller set points(contains OLTC tap position, SVC's set points and DG's P&Q set points) that are visited by the token prior to the present node. Figure 19 shows the simple passage sequence of the token between the nodes and the data that is exchanged during the passage.

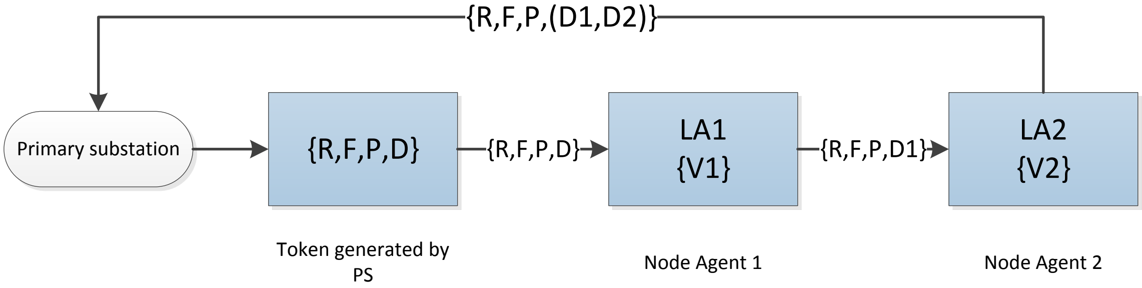

Figure 19 Example of token contour from two node network

In the above figure, $V1$ and $V2$ are the voltages measured by the LAs for comparison with the reference value of the token.

Communication between the load nodes and controller nodes strictly follows the flat architecture. When the token has made the contour of the whole network, it returns to the primary substation with the voltage value of each node in the form of inventory and the set points of the voltage control entities. As tokens are generated at each time step and circulate through the network recursively, they can also be used to detect the changes that are made in the network due to some fault or rearrangements in feeders. So network topology analysis can also be consummated with the token repetitive movement through the network.

5.3 Inter-agent Communication

All the agents that are utilized in the proposed method have some specialized inputs and outputs depending upon which they make their respective decisions and take actions which constitute the whole control procedure. They have their own specific goals which must be fulfilled, having a little importance to the MAS specific goal.

5.3.1 OLTC Agent

Mainly, OLTC has three goals:

- Tap changing depending upon the voltage value
- Keeping the tap count as minimum as possible, as excessive tap operation calls for repair.
- Token generation at each time step

Depending upon the communication between the OLTC agent and LA, inputs and the outputs of OLTCA are:

Table 1 Inputs and Outputs of OLTC agent

Inputs	*Outputs*
• DG Q-support limit reached (YES/NO) • Voltage deviation	• OLTC control availability(YES/NO) • Token at each time step

OLTCA belongs to the deliberate layer of the agent communication hierarchy because it generates token and set parameters and permission criterion for all the LAs and QCAs. OLTCA is contacted only when DG is not able to make changes in voltage, with only reactive power control. Voltage deviation makes distinction between under and over voltage to make tap operation relevant to voltage fluctuation. OLTCA will specify whether OLTC will be feasible or not (limited by minimum and maximum tap positions) and revise the tap position in token memory that will help LA in making decisions related to the real power curtailment of DGs if OLTC control is not applicable.

5.3.2 Q-Control Agents

Primarily DGs and SVCs are the control devices whereby agents are associated. Irrespective of the Q-controlling devices, the main responsibilities of QCA's are set point selection based on voltage fluctuation and in case of DGs, real power generation at maximum. Specifically in DGs, Q/V-droop control is preferred but if voltage violation is not completely tackled by OLTC and reactive power support, then P/V droop control is inevitable.

Co-ordination signals between QCA and LA distinguish inputs and outputs that are depicted below:

Table 2 Inputs and Outputs of Q-control Agents

Inputs	*Outputs*
• Voltage deviation • P/V control required (YES/NO)	• Q/V control availability (YES/NO) • P/V control availability (YES/NO) • Q-set & P-set (specifically for DG)

When QCA receives the voltage support message from LA, it will make the set point changes (if capable of providing support) and reply with set points and the notion of Q-control capability. LA based on that reply from QCA will make decision whether to contact OLTCA or stick with the QCA reactive power control capability. If both mentioned controls are not appropriate to eradicate the problem then P/V control support message will be transmitted by LA to QCA, which is not preferred in normal circumstances.

5.3.3 Load agent

In most of the publications that are reviewed, LA is modelled with only voltage monitoring capability. While the proposed algorithm includes the decision making unit in LA that deems it able to choose the rightful controlling device by cross-communication at each time step, making the system fully distributed.

Load agents inputs and outputs are depicted in Table 3:

Table 3 Inputs and Outputs of Load agent

Inputs	***Outputs***
• Q/V control availability (YES/NO)	• Voltage deviation
• Q-set & P-set (for DG)	• DG Q-support limit reached (YES/NO)
• OLTC control availability(YES/NO)	• P/V control required (YES/NO)

LA primarily belongs to the reactive layer and act as the main control entity, whose decision making capability holds voltage within statutory limits by manipulating all the control variables in their defined limits. It not only keeps in contact with the QCAs but also have the fair idea of OLTC operation capabilities. Having the knowledge of respective set points and the capabilities, the agent makes decision to invoke which controller in which scenario.

5.4 Proposed Algorithm

The steps of co-ordination between agents and decision making in the whole control procedure are described as follows:

1. Each LA measures the node voltage at each time step and keeps its measurements up-to-date.
2. The token is generated by OLTCA at each time step for voltage violation detection and to monitor any changes in the network. It moves from node to node for appraisal of voltage value. Once the breached node is detected, the token gives permission to the LA of the respective node to contact the controller device under which jurisdiction it lies. LA looks for the voltage support controller in DF and sends Voltage Support Request (VSR) to it in the form of voltage deviation value.
3. Once the controller receives the VSR, if the controller is capable of voltage support, it will make changes in its set points depending upon the type of violation (under voltage or over voltage) and reply with the set points value to the LA.
4. LA will compare the revised node voltage with the token's reference value. If voltage is within limits then the token will move on to the next node with the updated set point values of controllers, otherwise it will again send the VSR to the same controller; if it has some capability remaining. Contrarily, it will contact the next voltage controller downstream of the previous one.
5. If all the downstream controlling devices are at their limits, then LA will contact OLTCA for voltage support by tap changing operation and terminates the token.
6. Once the OLTCA receives VSR from LA, it makes adjustment in the tap position and regenerates the token. Token will follow the steps from step 2.
7. If OLTC reaches its extreme value (maximum or minimum tap position) and the reactive power support capability of controllers is also not available, QCA will receive VSR from LA with permission to curtail the real power of the associated DG.

8. When the token will reach the last node and all node voltages are within limits, then it will return to OLTCA with the knowledge of the networks node voltages and set points of controllers.
9. OLTCA has the final check on the node voltages and it waits for the next time step for token generation.

The flow diagram of the algorithm proposed is shown in Figure 20.

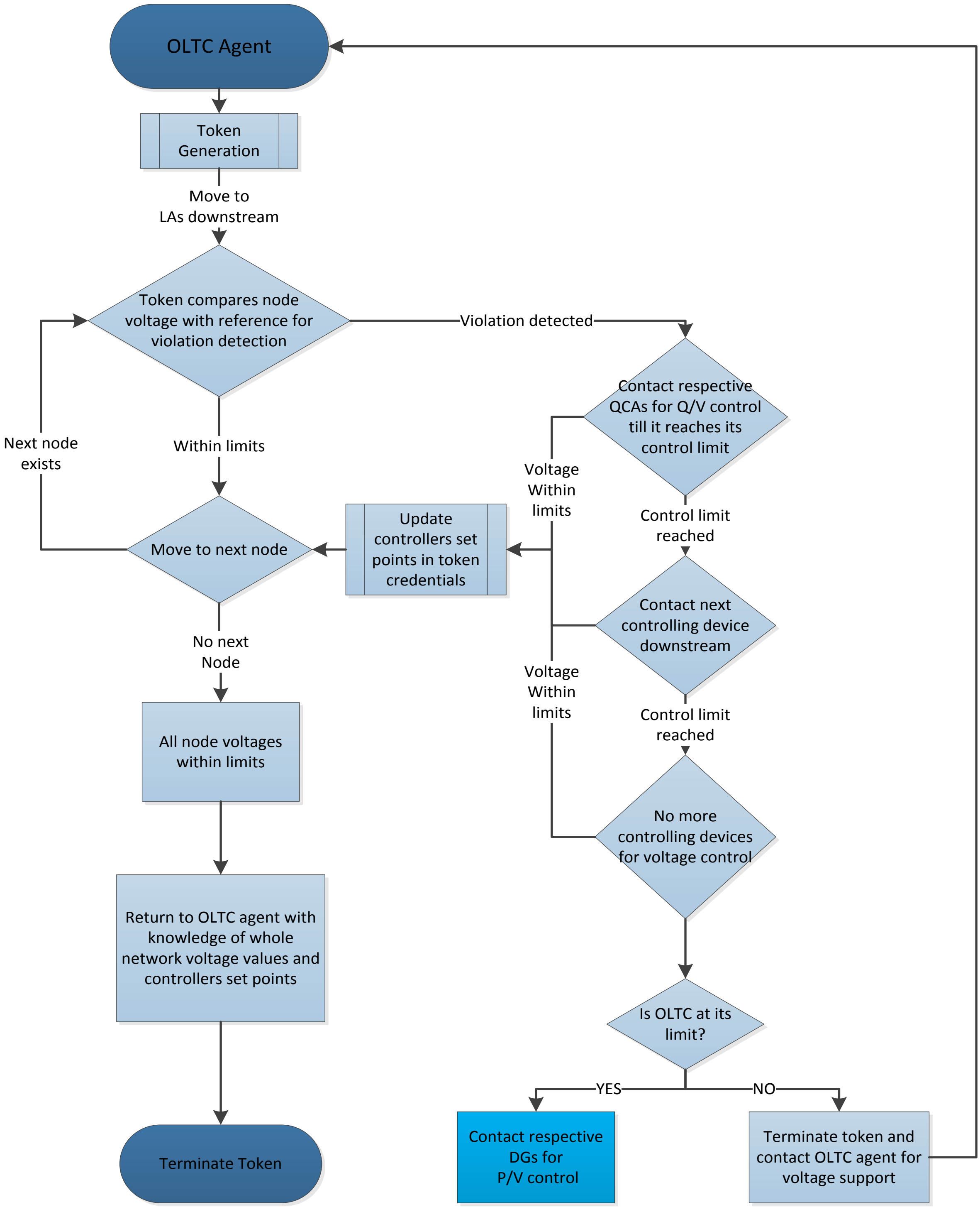

Figure 20 Flow diagram of distributed voltage control based on agents

The algorithm suggested for distributed control based on agents fairly uses the autonomous behaviour of agents and constructive interaction between the token and agents. The different control region based on network topology and controller agent's location is defined in the DF. DF log helps the token and the load agent to decide which controller should be contacted for the respected violated node. Voltage support controller is able to control the node voltages that are downstream to it, till the last node. Still, if the violated node lies in the vicinity of more than one controller then the controller closest to the node will try to remove the problem.

The idea of control region of different agents is depicted in Figure 21.

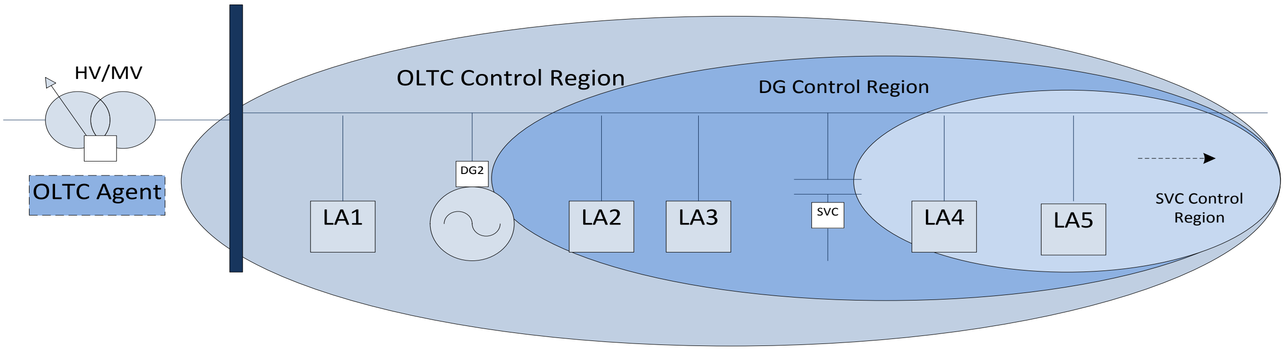

Figure 21 Voltage control regions for respective controllers

For instance, voltage boundaries are breached at LA2; the algorithm suggests that DG2 should be contacted for voltage support prior to communication between SVC and LA2 agents. OLTCA has control over the whole feeder so its operation should be given the last preference in voltage control strategy by the violated load agent.

5.5 Penalty Function Implementation

When the proposed algorithm is used for voltage control, probability exists, at some nodes of the network, for the voltage value settlement at extreme values (close to the cut off limits). Moreover, loss cost optimization is one of the objectives to be fulfilled that has a lot of significance. For the fulfilment of these objectives, a penalty function is to be defined whose application not only removes the high voltage at nodes but also tries to minimize the loss cost by aiding in the decision making procedure of stricter voltage limits (closer to the nominal).

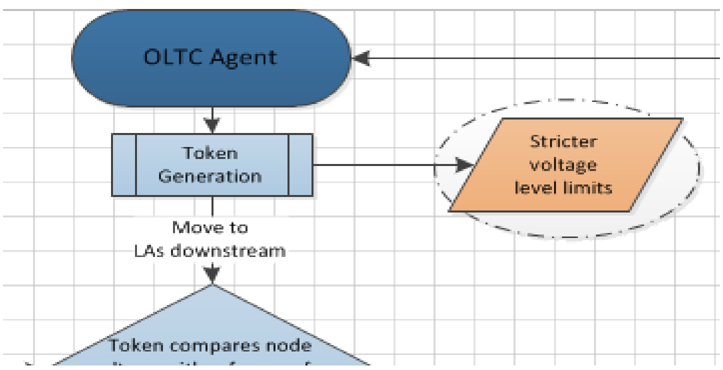

Figure 21 Changes in Algorithm with Penalty Function inclusion

There are two types of penalty functions; interior and exterior. Exterior penalty function tries to keep the optimization function within viable boundaries, starting from outside the feasible region, while trying to converge at some optimized point within the suitable limits. However, that is not the case with the interior penalty function, in which the best solution is to be found within the viable region, starting and ending points never leave the feasible region [45].

For penalty function implementation, no new algorithm is to be proposed. If the voltage reference value in the token data is changed to some stricter limits (values closer to nominal), and dependent on the voltage value implied a feasible solution will be obtained, with eradication of the high voltage level at the customer premises and the minimum losses in given scenario.

Penalty function calculations are made by the OLTCA, which acts as the supervisory agent, which will make the decision of the stricter limits; in order to minimize the network losses cost, DG curtailment cost and voltage damage caused due to the implication of penalty function. The total loss for various stricter voltage limits will be calculated and the ones with the minimum loss will be implemented through token transversal of the whole system. Figure 22 gives the generic idea about the behaviour of loss and voltage damage with varying voltage limits. The total loss of the system will take the form of bathtub curve, implying that the losses will be higher when the voltage limits are at extremes; maximum or minimum and approaches the minima around the cross-section of loss and voltage damage curves.

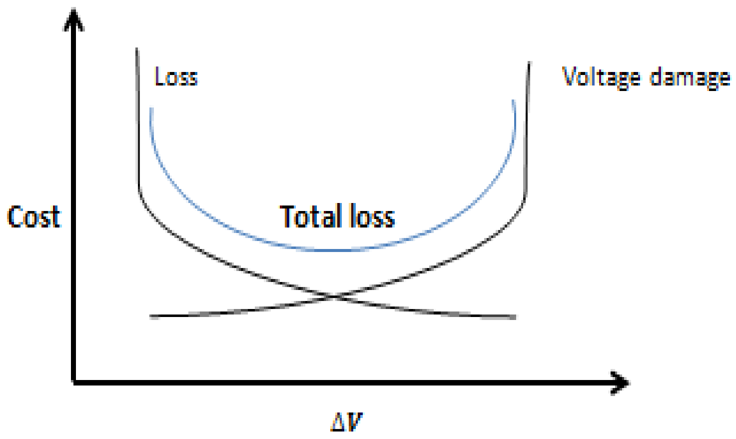

Figure 22 Network losses with varying voltage limits

Where

- *Cost:* In Euros
- ΔV : Voltage limits variation
- *Loss:* Network Loss +DG_{curt} loss
- *Voltage damage:* Loss due to voltage variation from the nominal
- *Total Loss:* Voltage damage + Loss

5.5.1Defined penalty function

Penalty function is defined in such a way that if voltage is within a small band closer to the nominal, the penalty will be zero. As the voltage values drift away from the nominal, the penalty imposed will get severe likewise. Voltage penalty function definition for limit violation is given by the following equation:

$$\begin{cases} P = k_p(V_{smin} - V)^2 & V < V_{smin} \\ P = k_p(V - V_{smax})^2 & V > V_{smax} \\ P = 0 & V_{smin} \leq V \leq V_{smax} \end{cases} \tag{12}$$

Above equation gives the penalty function with its stricter limits closer to the nominal. V_{smin} and V_{smax} gives the nominal band boundaries, while V gives the value of node voltage at a particular instant and k_p signifies the penalty factor. The graphical representation of voltage penalty function is given in Figure 23.

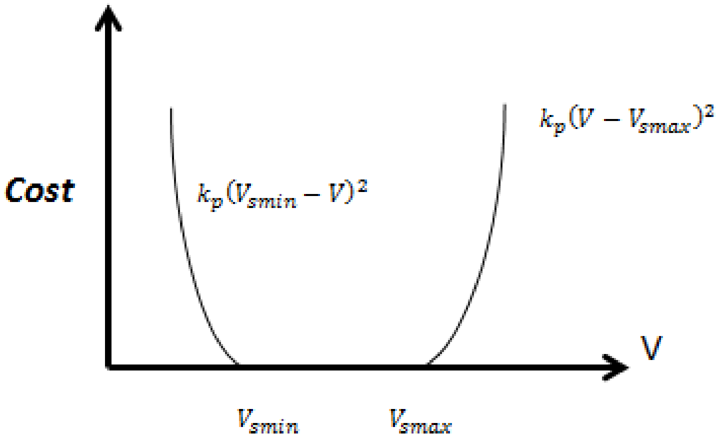

Figure 23 Voltage penalty function

However, with penalty function implication, there are some trade-offs that are imminent, for example:

- The network loss increment due to ancillary reactive power absorption
- The excessive real power curtailment of DGs

In contrast, voltage damage cost is reduced due to the voltage value settlement closer to the nominal value. Total loss optimization will reduces the overall losses cost that is one of the objectives

5.6 Characteristic features of the proposed technique

The novel approach to voltage control in the distribution system described in the thesis has the features that make it distinguishable among the previous works, which are:

- Token's ability to pass data between the stations and keeping the data of each node it visited, makes this approach more robust and sovereign in making decisions and fulfilling them.

- As the token keeps track of the nodes visited, so it will not take actions on the same node more than once.
- As each control entity's territory is predefined for violations at nodes, less communication overhead is required; no communication with the central system for permission and respective control device location.
- The system is divided into different control regions and communication between agents does not follow any particular hierarchy that makes the proposed approach truly autonomous and least liable to single point failure.
- Proposed scheme is basically designed for the radial system but it can be extendable to the more complex networks, due to its flexibility and protractible nature.
- LAs are equipped with decision a making unit, which is missing in all the previous researches.
- The final voltage values of the nodes settle closest to the nominal value, due to OLTCA's losses and voltage damage optimization.

Chapter 6

Case Study

6.1 Test Network

A Greenfield distribution network plan, based on realistic loading data and original geographical locations is utilized for the verification of proposed scheme, which is originally published in [44]. It is basically a Medium Voltage (MV) radial network with both underground and overhead lines including 146 nodes representing secondary substations (20/0.4kV) and a focal point representing the primary substation (110/20kV). The network is shown in Figure 24.

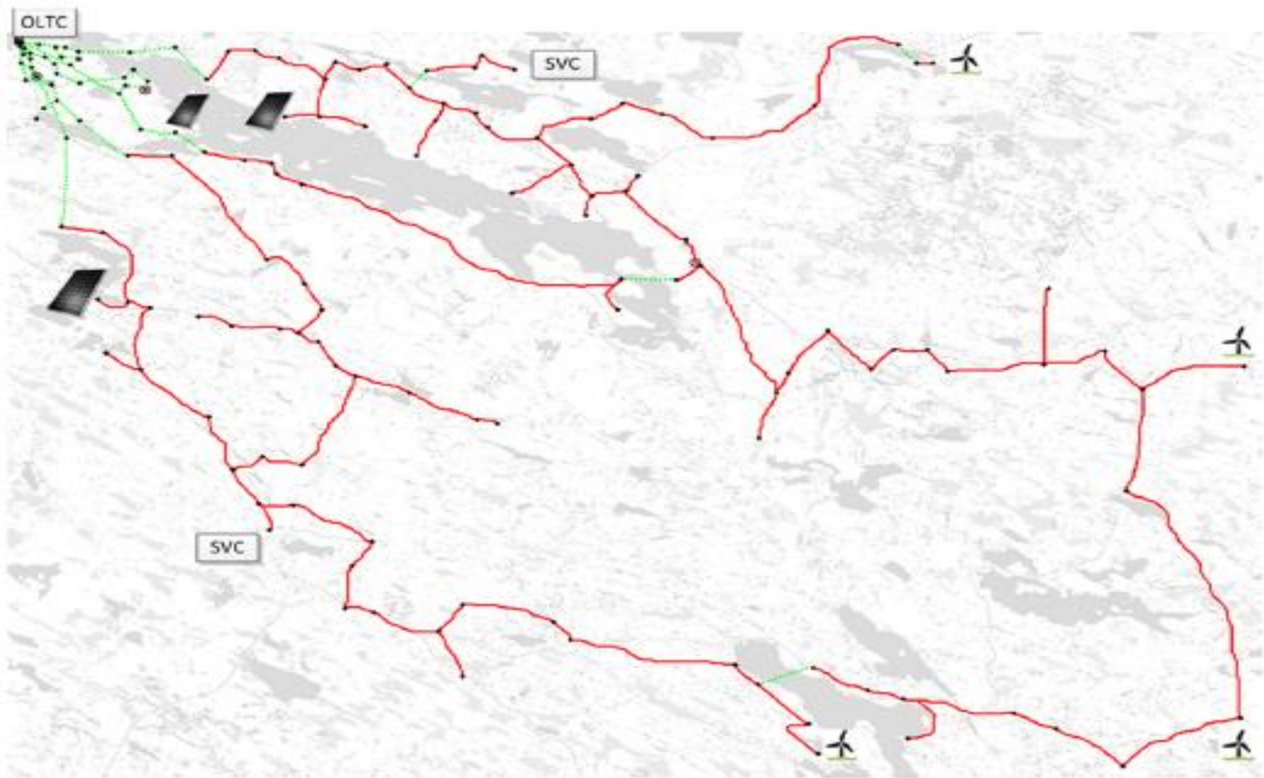

Figure 24 Greenfield network based on realistic loading data and geographical locations

There are altogether 7 branches originating from the primary substation, which comprises 30 radial feeders of varying lengths, the longest of which last for 60 km and 1.5 km is the shortest stretch. Technical details of the test network are given in Appendix A. Green lines represent the underground cables, while overhead lines are the red ones.

OLTC, at primary substation has the maximum and minimum tap value of $1.1\,pu$ and $0.9\,pu$ respectively. DG units and SVCs are placed at the load centres so that they can actively mitigate the voltage deviation problem with maximum efficiency. Total of four wind turbines, three PVs and two SVCs of varying real and reactive power capabilities are placed in the distribution system. Ratings of DGs and SVCs are given in Table 4.

Table 4 DG and SVC rating and node attachments

Controller	Node	Rating
WIND	66	50kW×3
	92	50kW×2
	102	50kW×2
	108	50kW×3
PV	28	215W/p×8
	83	215W/p×32
	117	215W/p×16
SVC	85	15 MVA
(0.005 pu/opp)	121	30MVA

The power system inherently happens to be non-linear. There are discrete controllers like SVCs and OLTC and continuous variables (DG's Q/V and P/V controls), but in this case study, SVCs are treated as continuous variable; steps of SVCs are taken to be very small for accurate voltage control. Moreover the load value that is chosen for each node is extracted from the pool of Automatic Meter Reading (AMR) data. Load is chosen for a particular day from the available data, precisely for 1st July, 12 pm. As for reactive power of loads, the power factor is considered between 0.95 and 0.98.

DG penetration level can be defined as *the ratio of annual energy production of DG to annual energy demand of the power system [43]*. This case study utilizes the penetration levels of 25%, 45% and 65% and helps in thoroughly investigating the proposed voltage control method. Study executed in this thesis takes the generation of DGs to be the maximum while a power factor value is set for having the reactive power absorption or injection capability. The test case is simulated in MATLAB with some assumptions related to agent's structure and communication.

Voltage values of the feeders of the distribution network, with varying distance from primary substation are shown in Figure 25 and 26, with and without DG respectively. Results of voltage value in Figure 25 depict the normal declining trend; the voltage value decrease as the distance from the substation is increased. The longest feeder has the lowest voltage value at the last node. While with the integration of DG, the voltage level at the farthest end of the distribution system is increased a lot as pictorially represented in Figure 26. In the DG integrated system, the main problem which is to be tackled is the over voltage. DG integration not only improves the voltage profile of the feeders (sometime the voltage goes way beyond the threshold value) but also decreases the losses in the system through proper integration points (load centres) in the distribution system which are quite valuable.

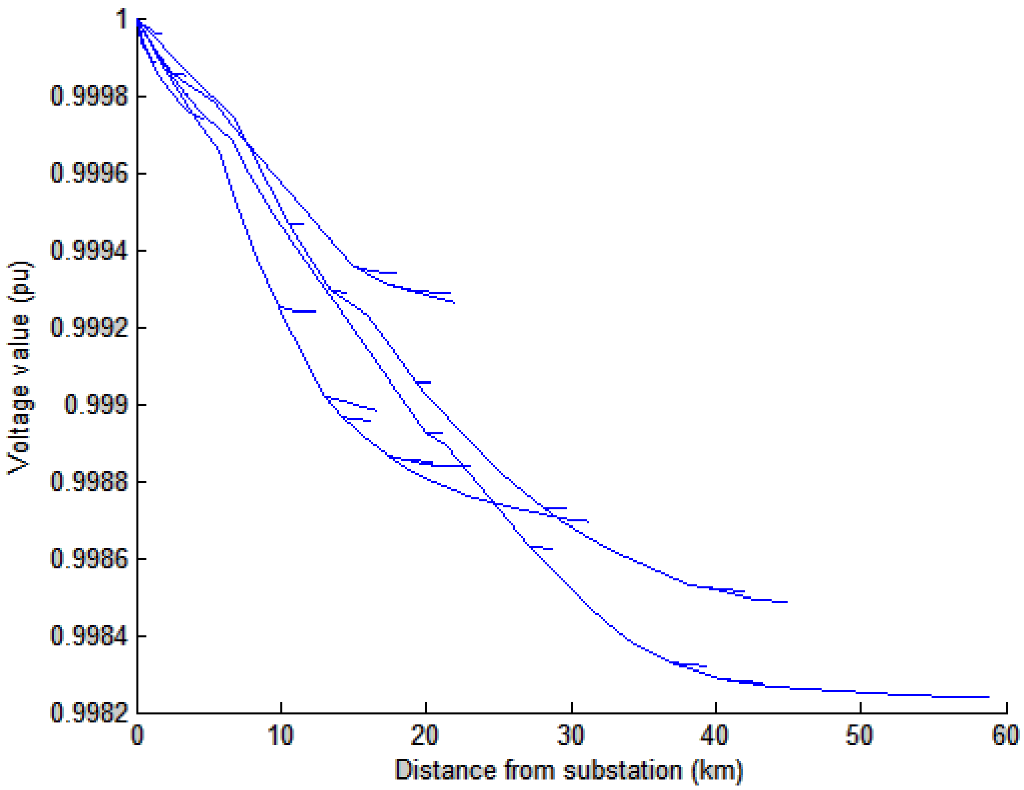

Figure 25 Voltage levels of feeders without DG

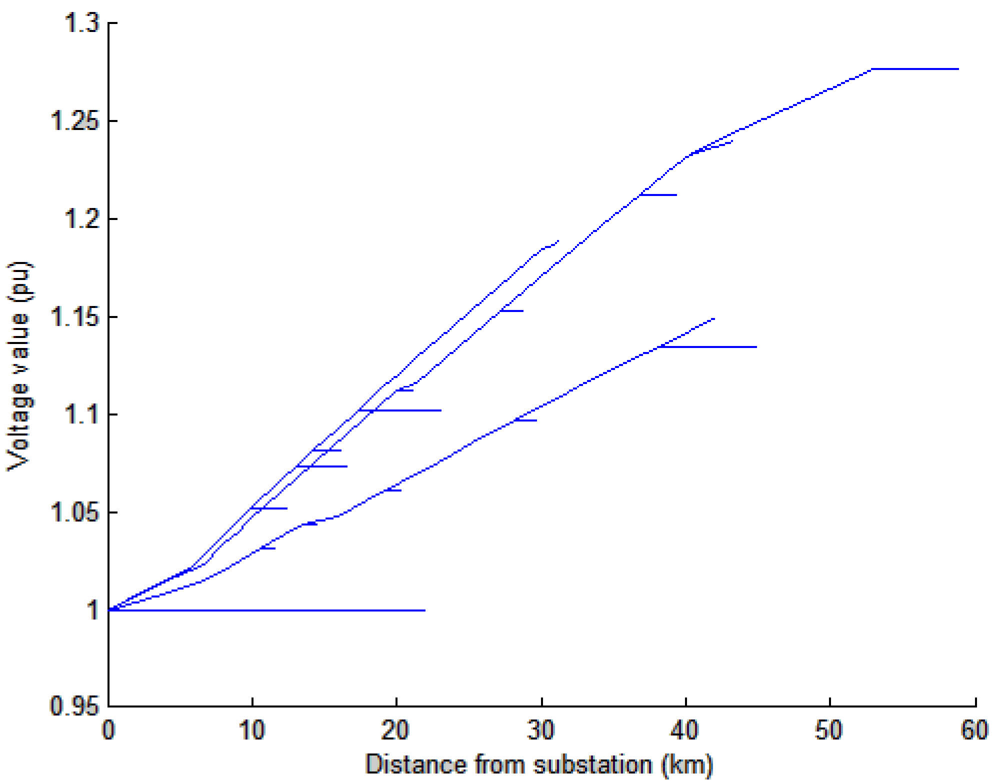

Figure 26 Voltage levels of feeders with 65% penetration

6.2 Case 1: Distributed Voltage Control (DVC)

DVC makes use of the algorithm that is defined in Section 5.4 for agent based voltage control. Varying DG penetration is studied for proper understanding about the agent's behaviour and control procedure's reliability. Different aspects related to the controlling devices and real and reactive power inputs of the controllers with DG penetration levels of 25%, 45%and 65% are briefly defined in the Table 5. The table mainly signifies the total number of SVCs, OLTC operations and cumulative reactive power absorptions or injection by SVCs and DGs, as well as P-curtailment and losses. For voltages and loss calculation simple DC-load flow is employed.

Table 5 Evaluation of DVC for varying DG penetration

Type of Control	DG penetration (%)	DG (P) curtailment (%)	Network Losses (kWh)	No. of OLTC operations	No. Of SVC operations	DG(Q) Generation (MVARh)	SVC(Q) Generation (MVARh)
DVC	25	0.2535	5.6448	0	0	-0.0016	0
	45	3.8562	6.7368	0	0	-0.185	0
	65	5.5521.	284.4	2	31	-0.324	-24

Figures 27a-27c show that the voltage levels of the feeders with DG penetration levels of 25%, 45% and 65% respectively. It is evident from the data in Table 5 and from figures that voltage control is quite effective for all penetration levels. OLTC and SVC operations in high DG penetration level increases, while losses show the rising trend by the reactive power absorption increment of SVCs and DGs. As the DG penetration increases, more real power curtailment is required for control.

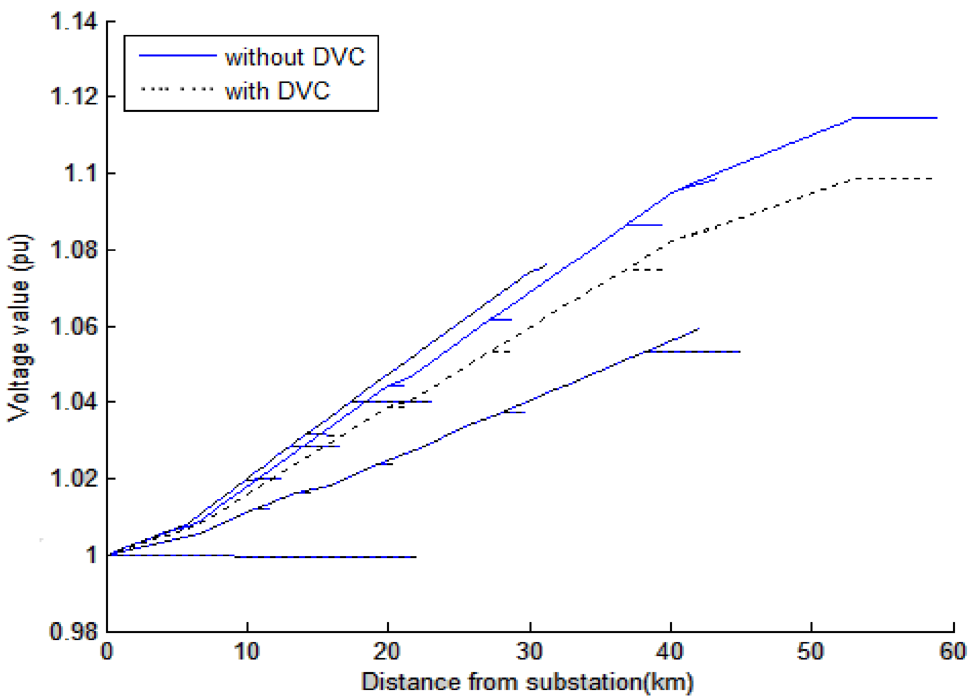

Figure 27 (a) DVC with 25% DG penetration

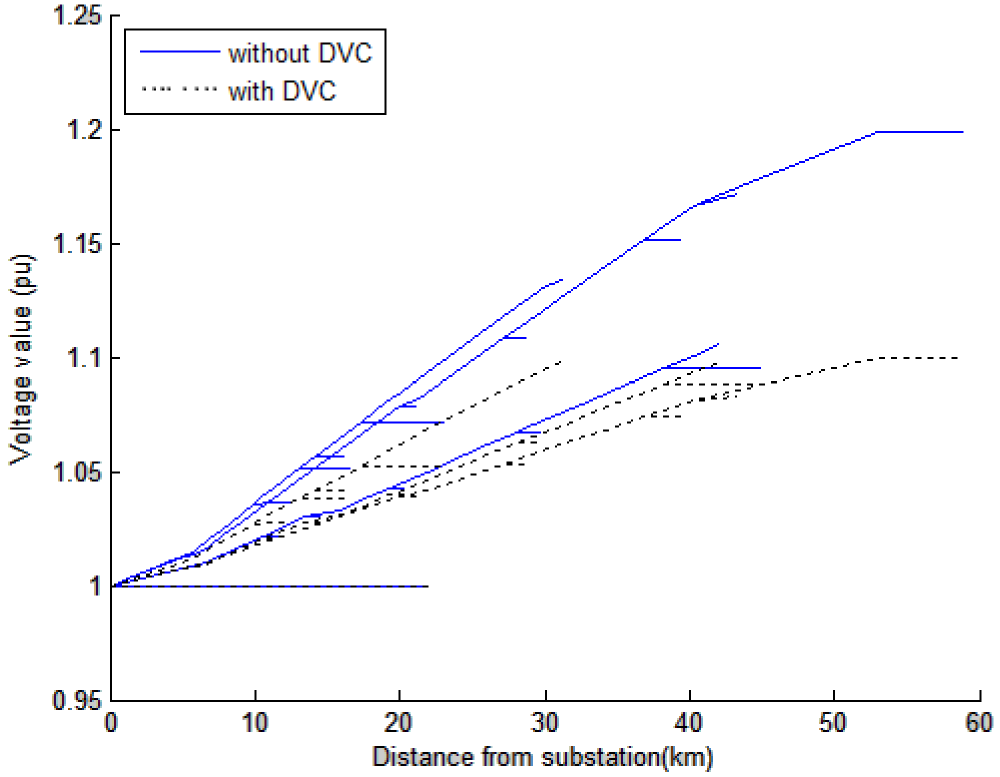

Figure 27 (b) DVC with 45% DG penetration

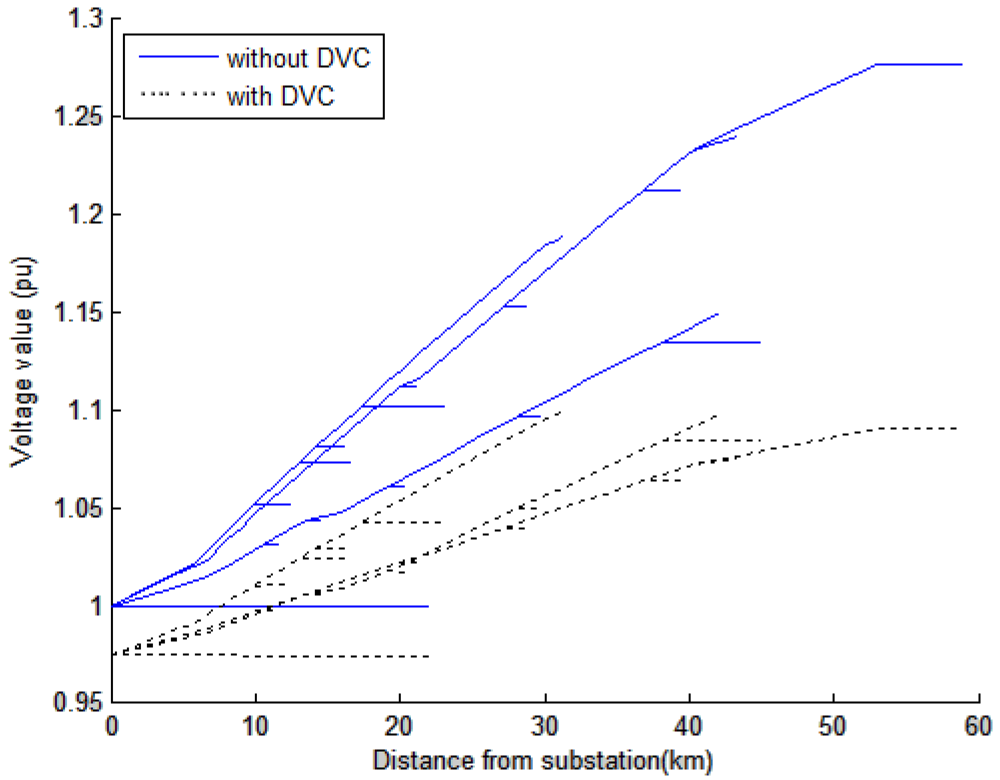

Figure 27 (c) DVC with 65% DG penetration

6.3 Case 2: Joint DVC and Penalty function

For joint DVC and penalty function case, the same DVC control is implemented with stricter limits (as close as possible to the nominal) based on the OLTCA optimization briefed in Section 5.5. In the study performed, seven different voltage bands are considered, which constitute varying ΔV as presented in the following table.

Table 6 Varying voltage limits

No.	V_{min} & V_{max}	ΔV
1	0.975-1.0125	0.0375
2	0.975-1.025	0.05
3	0.95-1.05	0.1
4	0.9375-1.0625	0.125
5	0.925-1.075	0.15
6	0.9125-1.0875	0.175
7	0.9-1.01	0.2

6.3.1 25% DG penetration

Losses variation with the voltage limit band (Figure 28) signifies that the losses will be high if the limits are too close or too far from the nominal voltage value. However, as the limit comes closer to the $\pm 5\%$ range, minimum loss cost is to be compensated by DNO. Eventually, OLTCA makes the decision based on the losses measured, as in this case any value around $\pm 5\%$ of the nominal voltage will be the one with the least possible losses.

Voltage values for all the feeders in the distribution network for 25% DG penetration with penalty function implication is pictorially depicted in Figure 29.

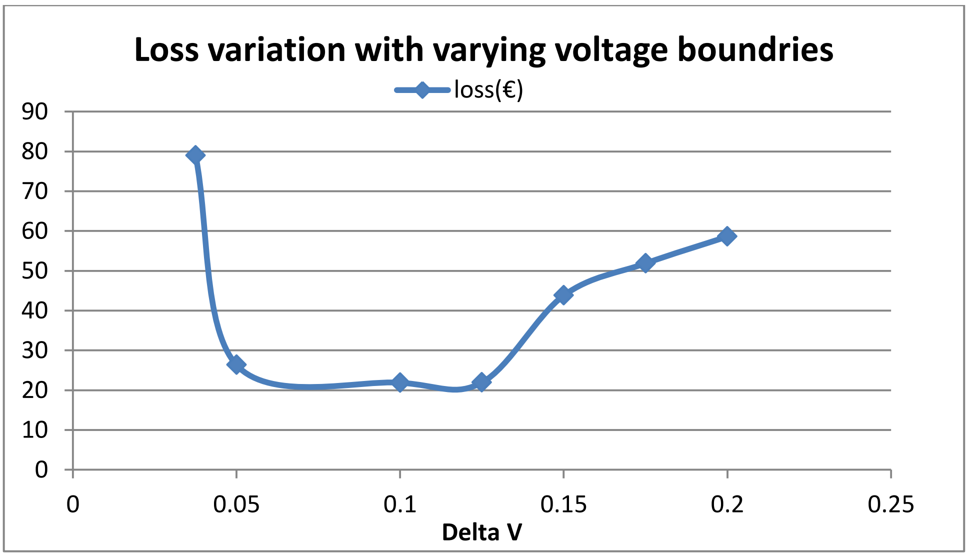

Figure 28 loss variation with varying voltage limits for 25% DG penetration

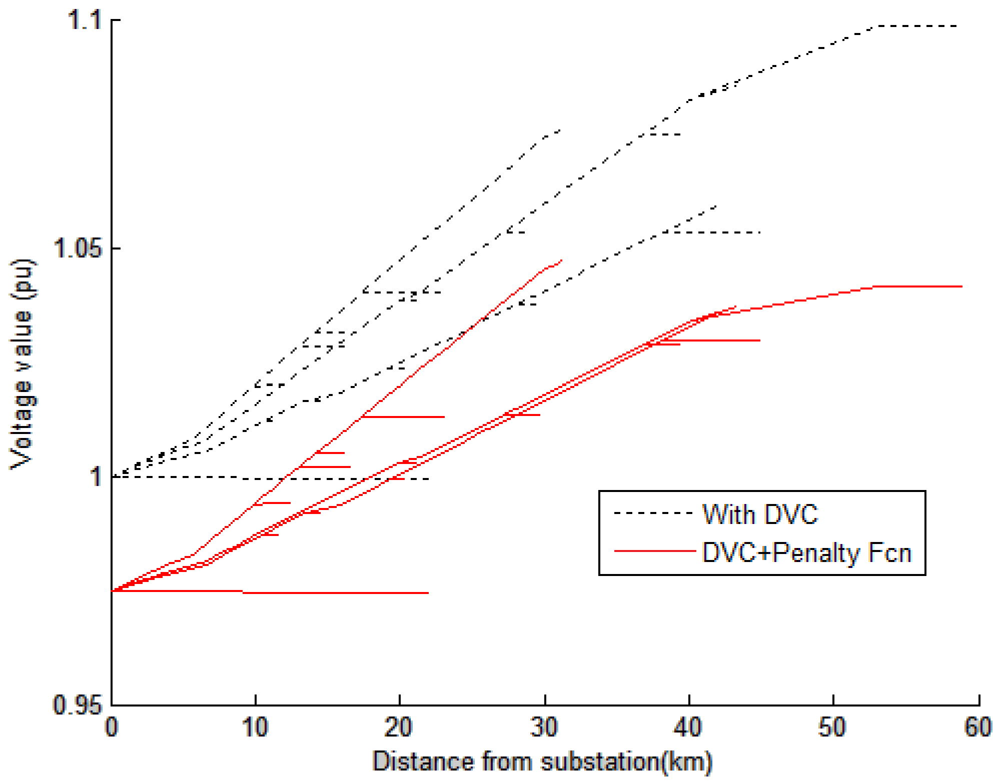

Figure 29 DVC+ Penalty function for 25% DG penetration

6.3.2 45% DG penetration

Again, losses give the rising trend in the extreme voltage limits (maximum or minimum), but the minimum loss is observed around $\pm 6.25\%$ of the nominal value (Figure 30). Furthermore, the minimum loss point is advanced towards the boundary of the $\pm 10\%$ value with increased DG penetration. The voltage level trend through all the 60 feeders with 45% of DG penetration level is shown in Figure 31.

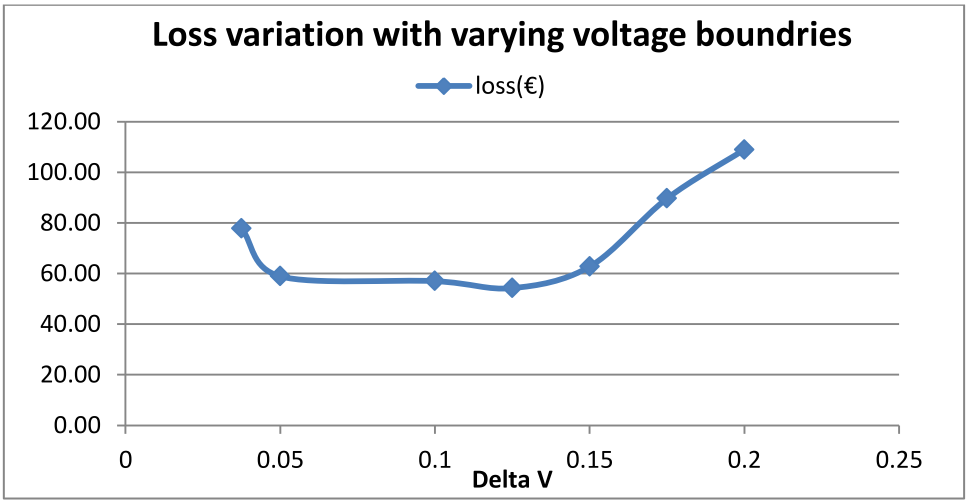

Figure 30 loss variation with varying voltage limits for 45% DG penetration

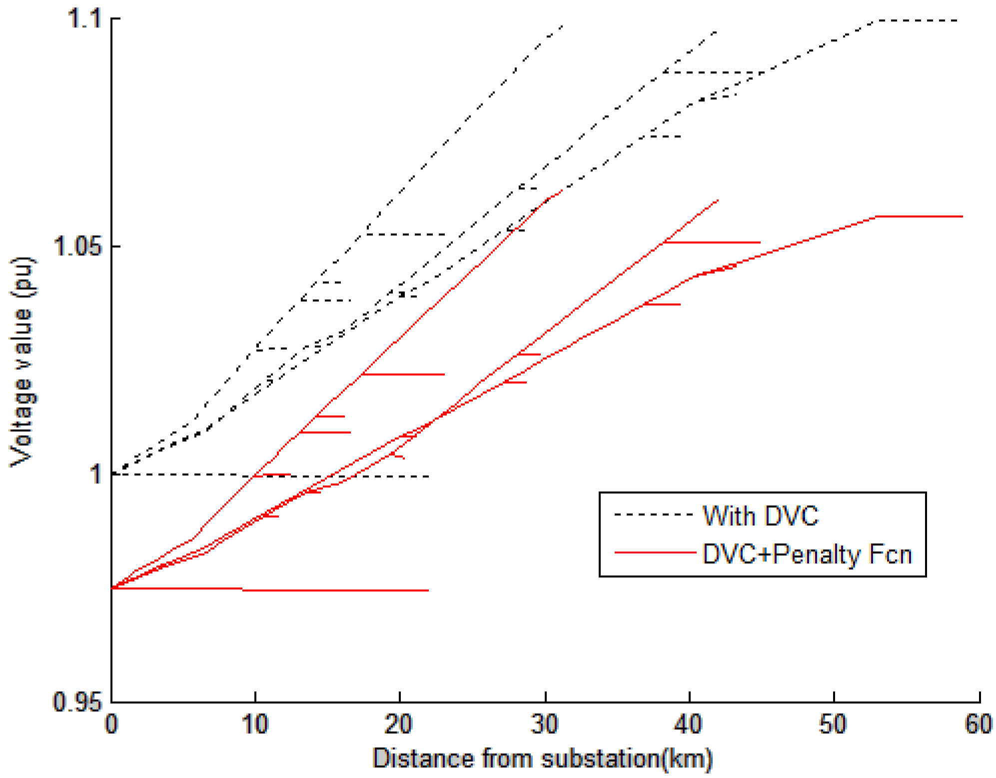

Figure 31 DVC+ Penalty function for 45% DG penetration

6.3.3 65% DG penetration

Notably, as the DG penetration increases, the loss graph (Figure 32) trend becomes more haphazard. At 0.1, losses are increased drastically with the decreasing trend on both sides onwards. If that abnormality is not taken into account, loss minimum is observed at ±8.75% of the nominal voltage value that is closer to the DVC voltage control limits. Voltage values throughout the network are evident from Figure 33.

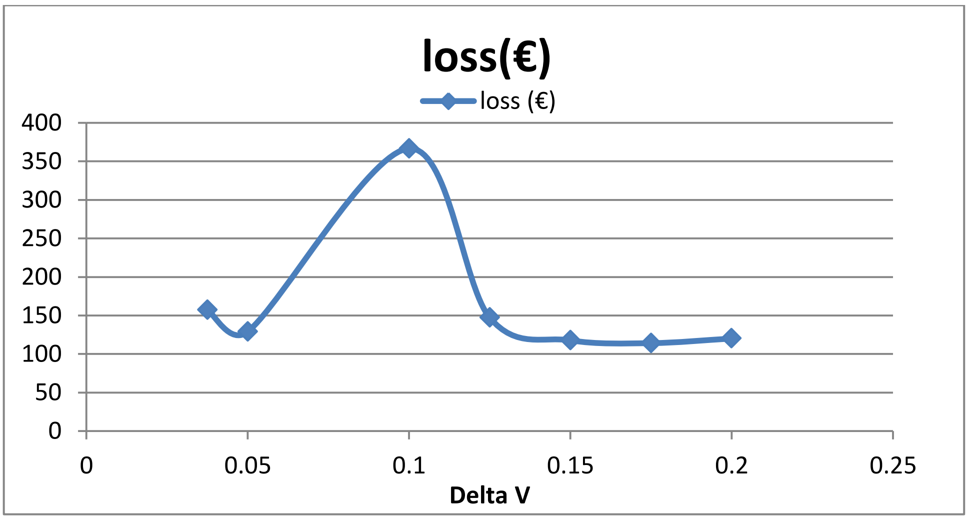

Figure 32 loss variation with varying voltage limits for 65% DG penetration

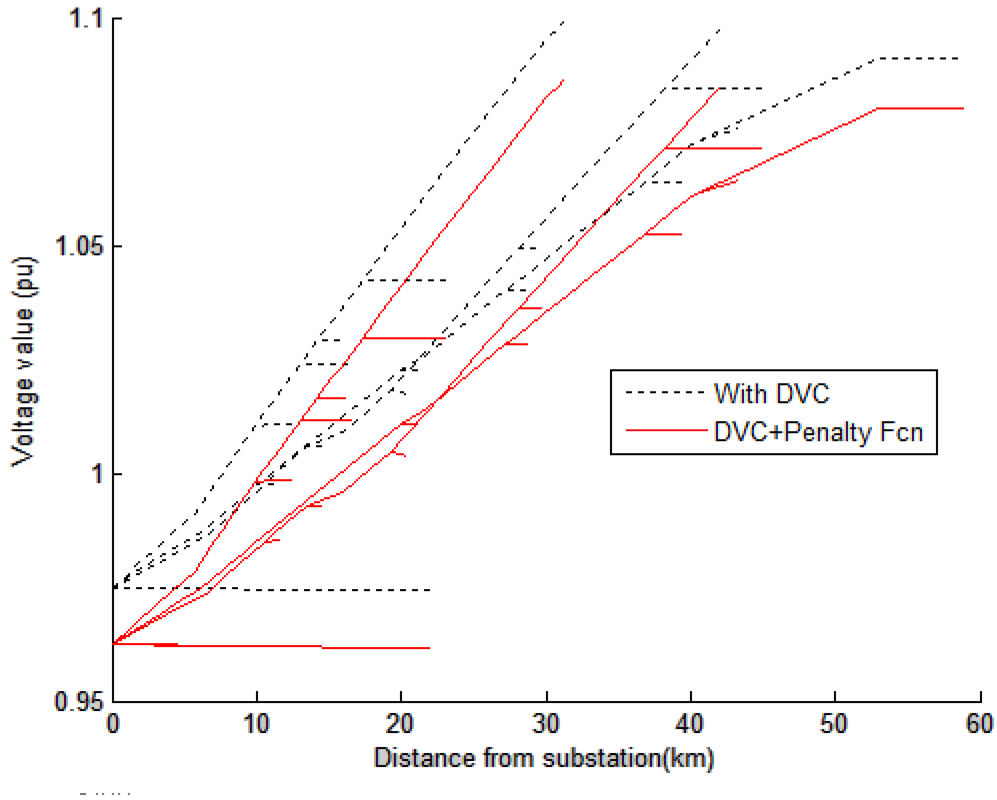

Figure 33 DVC+ Penalty function for 65% DG penetration

Based on optimization and resultant stricter limits to varying DG penetration levels, Table 7 gives the details of the controller set points, operating values and losses for joint DVC and penalty function case.

Table 7 Evaluation of joint DVC and Penalty function objective for varying DG penetration

Type of control	DG penetration (%)	ΔV	DG (P) curtailment (%)	Losses (kWh)	No. of OLTC operations	No. Of SVC operations	DG(Q) Generation (MVARh)	SVC(Q) Generation (MVARh)
DVC	25	0.1	2.4750	19.056	2	1	-0.0035	-4.8
+	45	0.125	5.4760	186.48	2	4	-0.2208	-19.2
Penalty fcn	65	0.175	5.55	421.08	3	32	--0.324	-28.8

6.4 Comparison between Case1 & Case2

Both cases are able to achieve their primary goals at the expense of available voltage control resources. Comparison between them is viable on the basis of voltage value within statutory limits, network losses and real power curtailment. Voltage control in DVC is superior to CVC in terms of maximum robustness and the need of minimum network data measurements required. With DG connection, loss reduction is a plus but control requirements at higher DG penetration levels show inclination towards higher losses.

In case 1, primary goal is to achieve the voltage value within the allowed band, irrespective of losses in the network and curtailment of DG with minimum latency. Moreover, the voltage boundaries are rather more expanded, so losses and curtailment of DG observed is less than the latter case. But voltage damage due to penalty function will be larger and have effect on the calculations of the total loss. Whereas, losses as well as DG curtailment show the increment as the power input from resources into the system increases (evident from Section 6.2).

Case 2 is employed with the objective of total loss cost decrement and improvement of voltage profile. With the penalty function implementation, a minimum of the system losses cost is worked out through obtaining the total loss curve. The normal trend to the set point of stricter limits is that as the penetration increases, minimum for losses cost is moving towards the expanded limits of DVC i.e. $\pm 10\%$ of the nominal.

Especially, DG penetration level increment makes the losses behaviour arbitrary with variant voltage limits. As the DG power input increases, for some of the voltage stricter limits, more number of nodes under the SVC control region are outside the allowable voltage band, which causes more operations; hence more losses are monitored along some stricter limits. Although the regular trend to the total losses is maxima at the extreme and minima around the cross section of voltage damage and losses curve, as pictorially represented in Figure22 of previous chapter.

The results indicate that costs of losses and DG curtailments are directly proportional to the DG penetration, while in case 2 there is a significant reduction in total loss. For lower DG penetration, losses are reduced more or less 50%, while for higher DG penetration, loss reduction is not very significant. Another observation is that the newer stricter limits calculated by cost optimization moves towards the statutory limits of ±10% of the nominal with the increasing DG penetration as for 25, 45 and 65% penetration, the optimized stricter limits are ±5, ±6.25 and 8.75% respectively.

Following Table 8 and Figure 34 gives the brief comparative results of the network loss cost, voltage damage cost and total loss cost for the two cases, with varying DG penetration, on monetary basis.

Table 8 Cost comparison of case 1 and case 2

DG Penetration	Case 1: DVC			Case 2: DVC-Penalty Function		
	Loss(€) (Network loss+DG curtailment loss)	**Voltage Damage (€)**	**Total Loss (€)** (Loss +Voltage damage)	**Loss(€)** (Network loss+DG curtailment loss)	**Voltage Damage (€)**	**Total Loss (€)** (Loss +Voltage damage)
25%	0.85	57.74	***58.60***	5.78	16.11	***21.90***
45%	12.615	96.34	***108.96***	30.3	23.95	***54.25***
65%	44.27	75.81	***120.075***	53.20	60.9	***114.10***

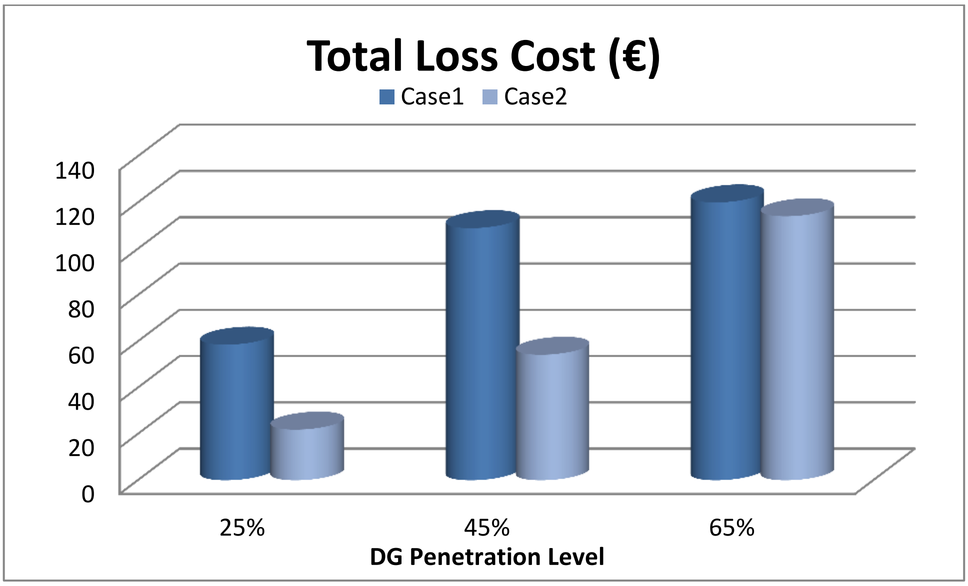

Figure 34 Loss comparison between cases

6.4.1 Benefits and liabilities

The proposed scheme is verified by its performance conferred in the previous section. Based on those results, suggested scheme can be well summarized under subheadings of benefits, liabilities and the data measurement required, which are the trademark of the DVC method approach taken in this thesis. Table 7 highlights the pros and cons that will be beneficial for DNOs and DG operators while making a decision about the appropriate control scheme.

Table 9 Summary of benefits, liabilities, required measurements and settings

Cases	Case1 (DVC)	Case2 (DVC +Penalty function)
Benefits	• Voltage level issue mitigation • Robustness • Simple control • Minimal time for decision making without central control supervision • Autonomous behaviour owed to agents	• Voltage value close to the nominal value (closer to flat curve throughout the network) • Total loss minimization due to loss cost optimization
Liabilities	• Q-control capabilities of DGs are limited by their size and power factor of operation • Extreme voltage values at some nodes in the network • Total loss cost is large	• Increment in Q transversal increase the overall network losses • DG P-curtailment is increased • Sluggish response due to iterative procedure • Large number of SVCs and OLTC operations

<table>
<tr><td>Required Measurements</td><td>Node voltages by LAs
Remaining real and reactive power capability of DGs by DG agents
Remaining Q-support available by SVC agents
OLTC taps availability by OLTCA</td><td>Node voltages by LAs
Remaining real and reactive power capability of DGs by DG agents
Remaining Q-support available by SVC agents
OLTC taps availability by OLTCA</td></tr>
<tr><td>Required Settings</td><td>Voltage reference settings in Token data
P&Q-settings of DGs
Q-settings of SVCs
OLTC tap settings</td><td>Stricter voltage reference settings in Token data
P&Q-settings of DGs
Q-settings of SVCs
OLTC tap settings</td></tr>
</table>

Chapter 7

Conclusion

In this thesis, distributed voltage control based on agents is devised, which successfully mitigate the problem of voltage deviation from the statutory limits. As the concocted procedure is distributed and autonomous entities are making instant decisions, the proposed method is superior to CVC in terms of quick response and computational overhead reduction. Moreover, the token based algorithm keeps the information of the network updated at each time step and has the knowledge of network's structure after transversal through it.

Based on the result observed in the last section, different phenomena are observed relevant to the voltage value and DG penetration levels. Though the normal trends are such as:

- As the DG penetration increases, voltage deviation from the limits increases as well.
- With the rising DG penetration, losses of the network, DG real power curtailment, OLTC and SVC operation increases for voltage violation removal.
- Penalty function implementation increases the network losses but the voltage value tries to settle down adjacent to the nominal value with least voltage damage.
- The minimum loss point, which was found by the intersection between the loss curve cost and voltage damage curve, tends to move towards the expanded voltage limits ($\pm 10\%$) with the increase in DG infiltration into the distribution networks.
- Stricter the limits for penalty function, larger will be the losses while voltage damage demonstrates the decreasing trend and vice versa.
- As the DG penetration increases, total losses cost does not follow the normal trend, but it becomes more arbitrary, which makes the total loss curve look random for some stricter voltage bands.

From the observed results stated above, it is devised that there are certain trade-offs that DNO has to make with voltage control problems. Decision related to prioritization of voltage level or voltage quality will have an effect on the network losses and control entities set points (DG curtailment).

In a nut shell, the focus of the thesis was on DVC based on agents, for robustness, least communication and computational overhead and decision based on fewer measurements of the network, which are fairly fulfilled. The main goal was to keep the voltage value within the defined limits. However, for cost effectiveness, a simple penalty function is applied that makes it easier to decide for the stricter limits, by the supervisory OLTCA, for voltage value closer to the nominal. The proposed algorithm is fully distributed for the main controlling action while penalty function based calculations are done by OLTCA processing unit, which makes the cost optimization process a partially centralized one or substation centred DVC architecture.

7.1 Future works

Active network management based on MAS is considerably a new concept in the power systems, especially in distribution systems. Most of the researchers are concentrating on devising the algorithms that are distributed, while neglecting the most important criteria i.e., the time domain implementation of the proposed scheme. Such implementation will demonstrate the practicality and issues that will be a hurdle while recommending the novel approach into the system hierarchy.

Moreover, in the case study conducted, agents are based on assumptions and coded in MATLAB, which does not fully demonstrate the ideal agent performance. For future works, agents can be developed based on the agent platform and utilizing the agent coordination language like JAVA, which will provide the full insight of the proposed scheme's robustness and effectiveness.

However, loss cost reduction is applied in the form of penalty function implementation, but the reactive power flow through the network is not subjected to any restraint. The only criterion that was monitored for the control was voltage value, irrespective of the amount of reactive power absorption and injection by SVCs and DGs. The loss cost, which the DNOs have to bear, will be greatly reduced if the reactive power flow through the network is minimized.

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APPENDIX A

Distribution Network Data (40 MVA base)

$No.$	$From$	To	$r(pu)$	$x(pu)$	$P_L(pu)$	$Q_L(pu)$
Branch No. 1						
1	1	6	0.003	0.003	0.001381	0.00029
2	6	30	0.003	0.002	0.002002	0.000508
3	30	34	0.006	0.005	0.000957	0.000245
4	30	12	0.002	0.002	0.00125	0.000353
5	12	29	0.005	0.004	0.001556	0.00042
6	29	20	0.005	0.004	0.000874	0.000261
7	20	4	0.01	0.008	0.000357	9.58E-05
8	4	23	0.017	0.014	0.000638	0.000149
9	23	40	0.005	0.004	0.000563	0.000137
10	40	35	0.007	0.006	0.001128	0.000301
11	35	26	0.004	0.003	0.000302	7.33E-05
Branch No. 2						
1	1	11	0.053	0.042	0.000293	0.000072
2	11	125	0.04	0.032	0.000111	0.000025
3	125	111	0.032	0.039	0.000047	0.000014
4	111	110	0.077	0.095	0.000127	0.000035
5	110	117	0.028	0.035	0.000061	0.000018
6	110	112	0.019	0.023	0.000129	0.000027
7	112	127	0.062	0.076	0.000072	0.000018
8	127	132	0.068	0.084	0.000069	0.000017
9	127	137	0.031	0.039	0.000062	0.000017
10	137	136	0.055	0.068	0.000035	0.000008
11	136	140	0.039	0.048	0.000039	0.000011
12	140	121	0.028	0.035	0.000080	0.000020
13	140	139	0.026	0.032	0.000170	0.000050
14	139	138	0.072	0.089	0.000073	0.000016
15	138	122	0.027	0.034	0.000025	0.000007
16	122	123	0.041	0.051	0.000080	0.000020
17	123	115	0.024	0.029	0.000077	0.000021
18	115	124	0.055	0.068	0.000076	0.000016
19	124	144	0.048	0.059	0.000013	0.000004
20	124	141	0.032	0.039	0.000140	0.000040
21	141	133	0.072	0.089	0.000056	0.000012
22	133	134	0.021	0.026	0.000068	0.000017
23	134	99	0.13	0.161	0.000032	0.000008
24	99	100	0.026	0.032	0.000028	0.000007
25	100	101	0.058	0.071	0.000030	0.000007
26	101	102	0.051	0.063	0.000098	0.000028
27	100	113	0.023	0.018	0.000013	0.000003

28	113	103	0.047	0.058	0.000043	0.000011
29	103	104	0.029	0.036	0.000101	0.000026
30	104	105	0.066	0.082	0.000100	0.000023
31	104	114	0.086	0.105	0.000041	0.000010
Branch No.3						
1	1	14	0.007	0.006	0.001011	0.000242
2	14	13	0.006	0.005	0.000533	0.000114
3	13	5	0.005	0.004	0.000502	0.000104
4	5	39	0.006	0.005	0.000461	0.000110
Branch No.4						
1	1	21	0.017	0.014	0.000141	0.000030
2	21	19	0.005	0.004	0.000185	0.000045
3	19	44	0.018	0.015	0.000401	0.000092
4	44	70	0.018	0.014	0.000209	0.000062
5	70	94	0.02	0.016	0.000133	0.000036
6	94	86	0.032	0.039	0.000039	0.000010
7	86	80	0.021	0.026	0.000529	0.000128
8	80	81	0.02	0.025	0.000165	0.000046
9	81	78	0.042	0.052	0.000143	0.000034
10	78	79	0.037	0.046	0.000056	0.000011
11	79	87	0.037	0.046	0.000045	0.000012
12	79	83	0.027	0.034	0.000083	0.000017
13	78	45	0.018	0.023	0.000004	0.000001
14	45	64	0.02	0.025	0.000055	0.000013
15	64	109	0.022	0.028	0.000061	0.000016
16	109	72	0.029	0.035	0.000157	0.000042
17	72	46	0.011	0.008	0.000103	0.000031
18	46	82	0.036	0.044	0.000080	0.000022
19	82	47	0.013	0.017	0.000066	0.000015
20	47	85	0.028	0.035	0.000238	0.000051
21	72	48	0.032	0.039	0.000102	0.000022
22	48	77	0.019	0.023	0.000037	0.000007
23	77	75	0.037	0.046	0.000171	0.000049
24	48	97	0.027	0.033	0.000031	0.000007
25	97	76	0.017	0.021	0.000075	0.000021
26	76	84	0.043	0.053	0.000058	0.000016
27	84	49	0.035	0.043	0.000055	0.000016
28	49	93	0.053	0.065	0.000031	0.000008
29	49	43	0.035	0.043	0.000001	0.000000
30	43	67	0.019	0.023	0.000083	0.000021
31	43	52	0.027	0.033	0.000029	0.000007
32	52	53	0.066	0.082	0.000022	0.000005
33	52	57	0.018	0.023	0.000061	0.000012
34	84	69	0.049	0.061	0.000034	0.000010
35	69	96	0.029	0.036	0.000014	0.000004

36	96	68	0.032	0.04	0.000030	0.000009
37	68	50	0.046	0.057	0.000157	0.000035
38	50	63	0.088	0.109	0.000045	0.000012
39	63	51	0.113	0.139	0.000117	0.000024
40	51	65	0.011	0.008	0.000074	0.000017
41	65	66	0.013	0.016	0.000035	0.000008
Branch No.5						
1	1	22	0.018	0.014	0.000452	0.000099
2	22	16	0.01	0.008	0.000924	0.000222
3	16	2	0.008	0.006	0.000033	0.000009
4	2	10	0.006	0.005	0.000189	0.000050
5	10	25	0.006	0.005	0.000295	0.000081
6	2	8	0.013	0.01	0.000428	0.000092
7	8	24	0.027	0.021	0.000053	0.000016
8	24	42	0.035	0.043	0.000154	0.000034
9	42	147	0.133	0.165	0.000021	0.000006
10	147	146	0.042	0.051	0.000027	0.000006
11	146	128	0.029	0.035	0.000070	0.000017
12	128	119	0.028	0.035	0.000076	0.000016
13	119	126	0.015	0.018	0.000191	0.000053
14	126	116	0.04	0.05	0.000137	0.000038
15	116	118	0.028	0.035	0.000012	0.000003
16	119	145	0.021	0.026	0.000176	0.000038
17	145	143	0.027	0.033	0.000024	0.000007
18	143	129	0.019	0.023	0.000012	0.000003
19	129	135	0.097	0.12	0.000054	0.000013
20	135	120	0.032	0.039	0.000226	0.000057
21	129	142	0.046	0.056	0.000111	0.000024
22	142	130	0.06	0.074	0.000035	0.000010
23	130	131	0.016	0.02	0.000056	0.000011
Branch No.6						
1	1	31	0.022	0.018	0.000648	0.000173
2	31	41	0.024	0.019	0.000207	0.000044
3	41	36	0.005	0.004	0.000714	0.000169
4	41	9	0.019	0.015	0.000227	0.000057
5	9	28	0.013	0.01	0.000149	0.000045
6	28	18	0.014	0.011	0.000089	0.000023
7	18	33	0.033	0.04	0.000008	0.000002
8	33	17	0.021	0.026	0.000102	0.000025
9	17	37	0.011	0.013	0.000221	0.000066
10	37	27	0.022	0.027	0.000098	0.000029
11	27	90	0.285	0.351	0.000032	0.000007
12	90	91	0.036	0.044	0.000075	0.000019
13	90	89	0.02	0.016	0.000097	0.000027
14	89	88	0.024	0.029	0.000035	0.000010
15	88	74	0.138	0.17	0.000039	0.000009

16	74	95	0.047	0.058	0.000073	0.000022
17	74	73	0.021	0.026	0.000011	0.000002
18	73	98	0.05	0.062	0.000136	0.000033
19	98	71	0.048	0.06	0.000079	0.000021
20	71	58	0.024	0.03	0.000069	0.000016
21	58	54	0.027	0.033	0.000048	0.000010
22	54	59	0.026	0.032	0.000230	0.000061
23	59	61	0.074	0.091	0.000073	0.000022
24	61	60	0.071	0.087	0.000107	0.000030
25	61	62	0.05	0.061	0.000000	0.000000
26	62	55	0.047	0.058	0.000166	0.000041
27	55	92	0.082	0.102	0.000057	0.000015
28	55	56	0.098	0.121	0.000061	0.000017
29	56	108	0.256	0.315	0.000041	0.000011
30	108	107	0.104	0.128	0.000024	0.000006
31	107	106	0.064	0.078	0.000005	0.000001
Branch No.7						
1	1	38	0.002	0.002	0.001193	0.000341
2	38	7	0.004	0.003	0.003282	0.000925
3	7	32	0.004	0.003	0.001316	0.000280
4	32	3	0.005	0.004	0.001392	0.000344
5	3	15	0.005	0.004	0.002075	0.000582